DEVELOPMENT AND EVALUATION OF THE COMBINED LOADING MODIFICATION TO THE V-NOTCHED RAIL SHEAR TEST METHOD FOR COMPOSITE LAMINATES

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

The objective of this research was to determine what modifications would be most effective in improving the loading capacity of the V-Notched Rail Shear test method. The new test method that was developed as a result of this research is known as the Combined Loading Modification to the V-Notched Rail Shear test method, or the Combined Loading test method. The Combined Loading test method modifies the current V-Notched Rail Shear test method by increasing the gripping region and the adding edge loaders similar to those used in the Iosipescu test fixture. To determine what modifications are most effective in increasing the loading capacity of the test method, finite element analyses were performed on v-notched shear specimens of different lengths and with different constraints. The dimensions in the gage section of the v-notched specimens of different length were maintained the same as the dimensions of the V-Notched Rail Shear specimens. These dimensions remained unchanged so that the highly uniform state of stress that exist in the V-Notched Rail Shear test method would still exist in any modifications.

Finite element analyses showed that the Combined Loading test produced uniform states of stress for three different composite laminates. Finite element models also predicted that Combined Loading test would produce a more uniform state of in-plane shear stress through the thickness of the specimen than the existing V-Notched test.

V-notched specimens of multiple lay-ups and thickness were tested in the current V-Notched test fixture as well as the Combined Loading test fixture. Two different lengths of specimens were tested using the Combined Loading test method. Results showed that the Combined Loading test using the longer specimens produced the most consistent shear strengths for similar laminates of different thickness.

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1. INTRODUCTION

As composite materials are used in applications requiring ever-increasing maximum strengths, the loads at which test methods used to validate these materials also increase. One area in which the load applications of composite test methods are continually increasing is shear testing. Shear testing of composites can be used to determine the in-plane shear properties such as the in-plane shear modulus or the in-plane shear strength, or it can be used to test the interlaminar shear moduli or shear strengths. For all of the shear tests available, there is no test method that is preferred for all shear testing.

One current method for measuring the shear properties of composite materials is the Iosipescu test (ASTM D 5379, see Figure 1.1) [1]. The Iosipescu test provides a highly uniform state of in-plane shear stress and is easy to use, but due to small gage section of the samples, it cannot be used with coarse weaves where the size of the unit cell is greater than the test region. Also, due to the method of loading, for high strength laminates the corners next to the gage section will crush prior to the specimen failing in the gage section.

For high strength laminates and coarse textile weaves that the Iosipescu test method is unable to produce valid results for, there is another shear test: The V-Notched Rail Shear test (ASTM D 7078, see Figure 1.2) [2]. The specimens in this test have a test region about three times as large as the test region in the Iosipescu specimens. Due to fact that the load is applied through frictional load plates instead of

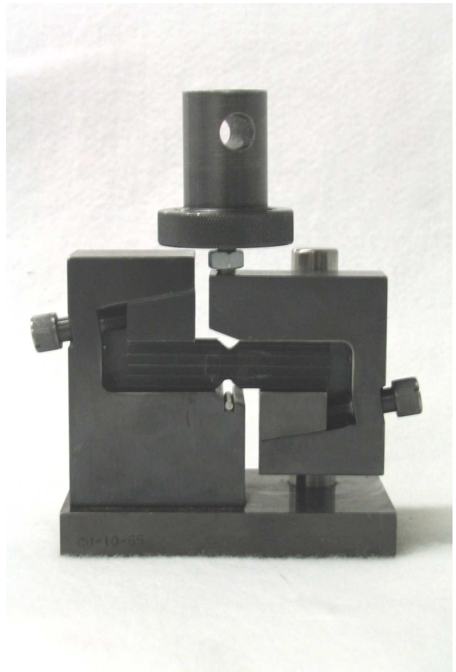


Figure 1.1 The Iosipescu test fixture

edge loading like the Iosipescu test, the corners do not crush and the V-Notched Rail Shear test method is able to produce valid test results for much higher shear-strength laminates.

While the V-Notched Rail Shear test (V-Notched test) also has a highly uniform state of shear like the Iosipescu, and it is able to test many high shear-strength composites as well as those with relatively course weaves, it has one deficiency. As it can be seen in Figure 1.2, the load is applied to the V-Notched specimen through the fixture by frictional load plates. A normal force is applied by the load plates onto specimen by three allen head bolts on each side of each half of the fixture. For very high shear-strength composites, specimens will sometimes slip inside the test grips prior to failure. If the specimen were to slip prior to failure then

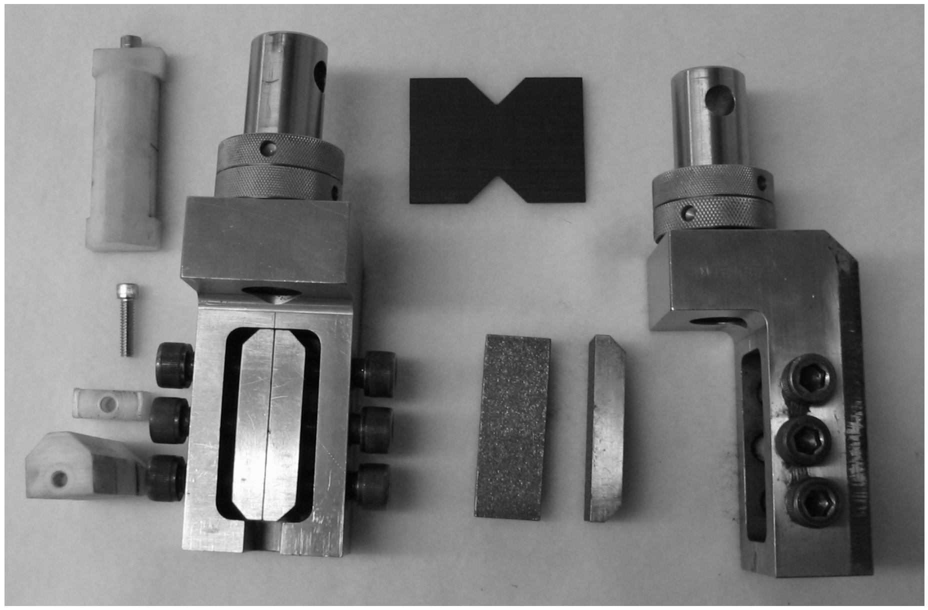


Figure 1.2 The V-Notched Rail Shear test fixture

the shear strength could not be accurately calculated and the test would be invalid. The emphasis of the present study is to develop a new shear test for high shear-strength composites that mitigates the deficiencies of the existing V-Notched Rail Shear test. A highly uniform state of in-plane shear throughout the test section was sought to exist in the same way that it does in the V-Notched and Iosipescu tests. The new test method was also designed to be able to test higher shear strength specimens without allowing the specimens to slip and without crushing the corners.

2. LITERATURE REVIEW

Shear testing of composite materials has been practiced for over fifty years. Through experience and with the aid of finite element analyses, shear tests have changed and evolved into the current shear tests that are used today. Many different published works have chronicled this evolution. The focus of this chapter is not to present a history of the evolution of composite shear tests, but to present the current ASTM shear tests for composite materials and explain their strengths and their limitations. For a comprehensive history of shear testing of composites, "The Wyoming-Modified Two-Rail Shear Test Fixture for Composite Materials," by Hussain and Adams is suggested [3].

2.1 Current Shear Test Methods

Currently there are many different shear test methods for composite materials. One of the most well known shear test is the Iosipescu Shear Test [1]. This fixture can be seen in Figure 1.1. This shear test is popular due to the uniform state of shear that exists between the notches and because of its ease of use. The limitations of the Iosipescu test are the small gage section that exists between the notches and the method of applying load to the specimen. The small gage section of the Iosipescu specimen makes it impossible to accurately test the properties of coarse textile composites that have a unit cell larger than the gage section. The Iosipescu test is also ill-suited to test composite materials with high shear strengths. For high shear strength composites, crushing will often occur at the corners near the gage section due to contact stresses caused by the edge loaders in the fixture.

Another well-known shear test method is the Two-Rail Shear Test Method [4]. The designation for this test method is ASTM D 4255. The specimens tested in this fixture measure 152 mm (6 in) high and 76 mm (3.00 in) long. They have three holes drilled into each side for securing the specimen to the fixture.

The use of holes drilled into the side of the specimen allows the fixture to secure the specimen well, but the use of holes can lead to bearing failure in specimens. Research done by Hussain and Adams [3] showed that replacing the bolts with flame-treated gripping plates that clamp the specimens similar to a C-clamp can yield valid results at loads that would result in bearing failures using the existing Two-Rail Shear fixture. The flame treated gripping surfaces are made by a thermal-spray treatment which creates a hardened surface that has a roughness similar to 60-grit sand paper. The use of the gripping plates in place of the bolts also reduces the manufacturing time of the specimens because the six holes for securing the specimens are not necessary.

While the Two-Rail Shear test benefited from the research done by Hussain and Adams, the test had other flaws. Research done by Adams et al. [5] showed that the state of in-plane shear stress in the two-rail shear specimen is considerably non-uniform. Their research also showed that the state of stress for the in-plane normal stresses is not negligible and that these stresses could contribute to the failure of the specimen. From their research, a new rail shear test method was developed, the V-Notched Rail Shear Test Method, ASTM D 7078 [2] (see Figure 1.2). The V-Notched

Rail Shear test method combines the favorable characteristics of the Iosipescu test with those of the Two-Rail Shear test. From the Iosipescu test it uses a similar v-notched gage section that has favorable state of stress for shear testing and from the Two-Rail Shear test it uses rough gripping surfaces to apply load to the specimen, similar to those used by Hussain and Adams in their research [3].

Finite element results for the V-Notched Rail Shear Test Method show that the in-plane shear stresses between the notches of the specimens are highly uniform and that the in-plane normal stresses between the notches are negligible [5]. The V-Notched Rail Shear test method also has a larger test region than the Iosipescu test method, and so it is able to test coarse weave textile composites that the Iosipescu test cannot. Experimental testing of the V-Notched Rail Shear test method also shows it is able to obtain valid shear test results for much stronger laminates that were not able to be tested with either the Iosipescu test method or the Two-Rail Shear test method [5].

The limitation of the V-Notched Rail Shear test method is that it applies load only through friction, and so it is limited in how much load it is able to apply to a specimen. For very high shear strength composites and for very thick composites, this test method is inadequate.

For this present study, improvements were investigated for the V-Notched Rail Shear test method with the objective of increasing the loading capability of the V-Notched Rail Shear test without affecting the state of stress in the gage section. The improvements investigated include an increase in length in the gripping region and new methods of constraining the specimens. For all of the improvements made, it was important that the state of stress between the notches not be adversely affected. For this reason, the dimensions in the test section of the specimens were not changed.

3. FINITE ELEMENT MODELING

3.1 Introduction

The finite element method was employed in this study in order to predict the most effective ways to solve the slipping problem that exists in the current V-Notched fixture. The finite element method was also employed in conjunction with mechanical testing to determine the coefficient of friction that should be used in the subsequent models.

It was proposed that increasing the gripping region of the specimens would reduce the amount of slipping that occurs, and also increase the load required for the specimen to rotate. Specimens with gripping regions ranging in from 12.7 mm (0.5 in) to 114.3 mm (4.5 in) were modeled and analyzed to determine the effects of increasing the gripping region.

Another method of preventing the specimens from slipping that was proposed was the addition of edge loaders similar to those used by the Iosipescu fixture (see Figure 1.1). A fixture that applies both face loading similar to the V-Notched Rail Shear fixture and edge loading similar to the Iosipescu fixture was modeled to investigate the effects of loading situations that exist in experiments. This new fixture is called the Combined Loading fixture. The results analyzed include the laminate effects (which were investigated to determine what the effects the new Combined Loading test method would have on different laminates), and the thickness effects (which were investigated to determine the uniformity of stress through the thickness of the specimens). Contour maps of different stresses and displacements were analyzed to determine what length of specimen and what method of constraining the specimens seemed most viable for solving the issue of specimens slipping.

3.2 Analysis Methodology

The finite element software used in this study was ANSYS Workbench student version 11.0 [6]. This particular software was selected due to its ability to easily create and use contact surfaces and elements. All of the models were three-dimensional. The size of the models ranged from the simplest and coarsest at 6,083 nodes and 1,592 elements to the most complex and refined using 39,753 nodes and 10,815 elements. The models were oriented so that the load is applied in the y direction and the length of the specimen runs in the x direction, as shown in Figure 3.1. Only half of the specimen and the fixture assembly were modeled due to symmetry. Because of the symmetry, only half of the load, half of the fixture and half of the specimen thickness were used in the models. Specimen models measuring 1.27 mm (0.05 in) to 6.35 mm (0.25 in) thick were used to model experimental specimens that would measure 2.54 mm (0.1 in) to 12.7 mm (0.5 in) thick respectively.

Multiple types of elements were used in these models. The structural elements used were a 3-D, 10-node tetrahedral structural solid element (Solid187) and a 3-D, 20-node structural solid element (Solid186). It is noted that these solid elements all have mid-side nodes. It is generally known that the use of mid-side nodes increases

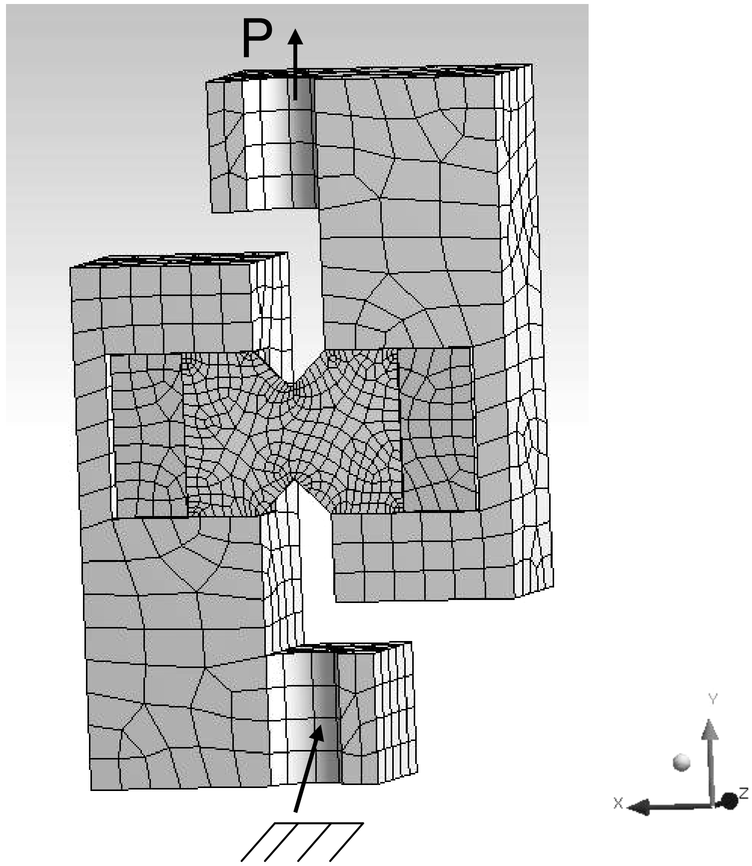


Figure 3.1 The orientation and loading conditions of the finite element models

the solving time of the finite element program, but it also improves the results without needing to greatly increase the number of elements.

The contact elements used were a 3-D target segment (Targe170) and a 3-D, 8-node surface-to-surface contact (Conta174). These contact elements are capable of modeling bonded, no-separation, rough, frictionless, and frictional contacts. In this model, they were used to model bonded, no-separation, frictionless, and frictional contacts.

Load was applied to the top half of the models in the positive y direction, as shown in Figure 3.1. The left half of the fixture assembly was fully constrained on the

25.4 mm (1.00 in) hole that is labeled in the figure. The backside of the model was constrained in the z direction to create symmetry.

Three laminates were modeled in this study. They are a cross-ply, a quasi-isotropic, and a ±45 lay-up. These three laminates are representative of all specimens tested experimentally. To model thicker or thinner specimens, the thickness was changed in the model, but the material properties were maintained the same. Table 3.1 shows the properties of all the materials modeled in the simulations.

3.3 Specimen Geometries Modeled

An initial investigation was performed to determine the coefficient of friction between the gripping plates and the specimens. The specimen that was modeled and fabricated for this study was essentially an ASTM D 7078 specimen without the V-notches. It is shown in Figure 3.2.

It was proposed that increasing the length of the gripping region, while maintaining the dimensions of the test region the same as those given in ASTM D 7078 [2], could prevent the specimens from slipping in the grips. The over-all lengths of the specimens modeled ranged from 50.8 mm (2.00 in) to 254 mm (10.0 in), moving up in 25.4 mm (1.00 in) increments with exception of the 63.5 mm (2.50 in) specimen. Figure 3.3 through Figure 3.7 show the current standard along with all of the other specimens modeled. It is important to note that the dimensions in the gage section do not change, only the length of the grip region changes.

Table 3.1

Material properties used in the finite element modeling

Application in Model	Material		Material Properties								
			E_x GPa (Msi)	E_y GPa (Msi)	E_z GPa (Msi)	G_{xy} GPa (Msi)	G_{yz} GPa (Msi)	G_{xz} GPa (Msi)	ν_{xy}	ν_{yz}	ν_{xz}
Specimen	IM7/8552 Carbon/epoxy	$[0/90]_{2s}$	88.25 (12.8)	88.25 (12.8)	13.51 (1.96)	49.64 (7.2)	4.21 (0.61)	4.21 (0.61)	0.041	0.41	0.41
		[0/±45/90]s	62.6 (9.08)	62.6 (9.08)	13.51 (1.96)	23.72 (3.44)	4.21 (0.61)	4.21 (0.61)	0.32	0.29	0.29
		$[\pm 45]_{2s}$	17.93 (2.6)	17.93 (2.6)	13.51 (1.96)	42.4 (6.15)	4.21 (0.61)	4.21 (0.61)	0.81	0.08	0.08
Test Fixture	Steel			206.84 (30.00)			79.55 (11.54)			0.3	

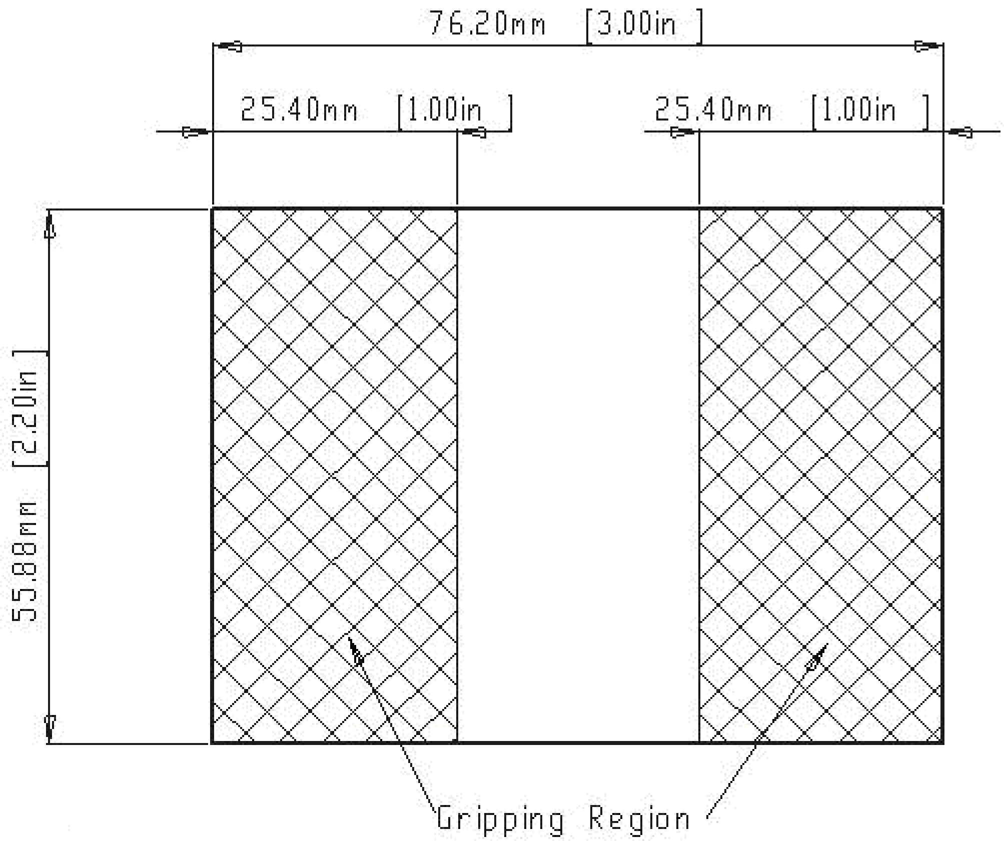


Figure 3.2 The friction test specimen

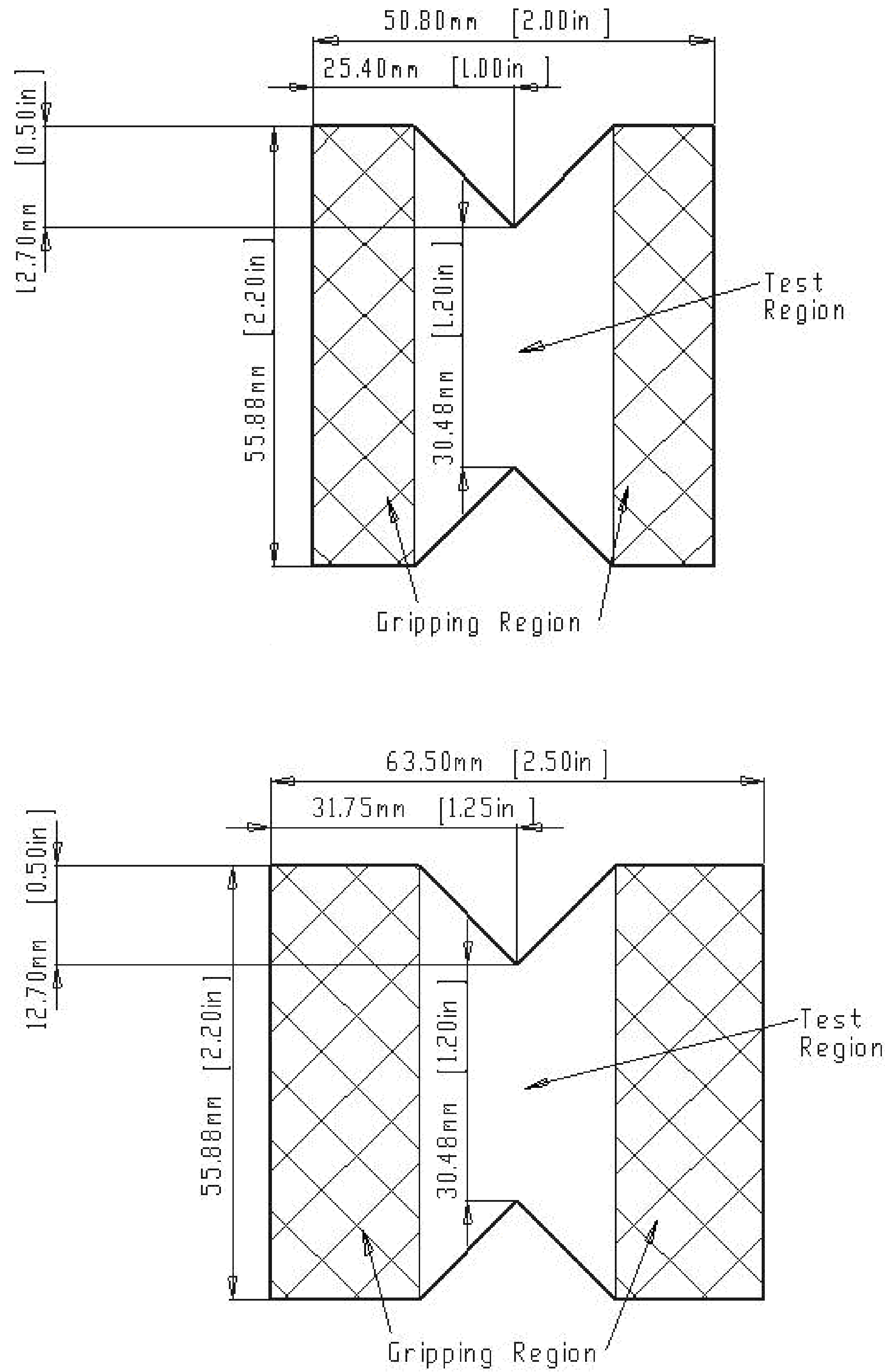


Figure 3.3 The 50.80 mm (2.00 in) and the 63.50 mm (2.50 in) long specimens

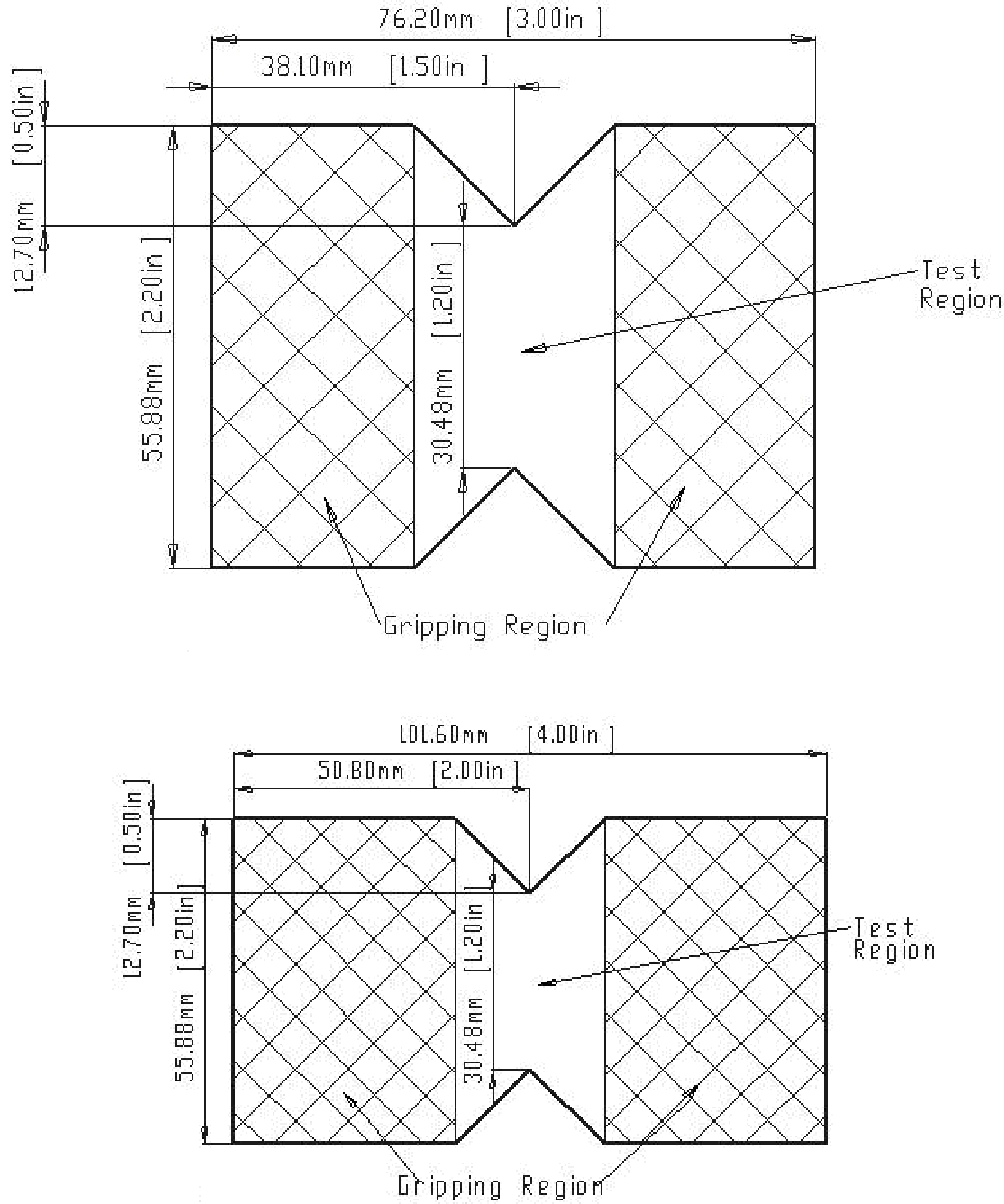


Figure 3.4 The 76.2 mm (3.00 in) and the 101.60 mm (4.00 in) long specimens

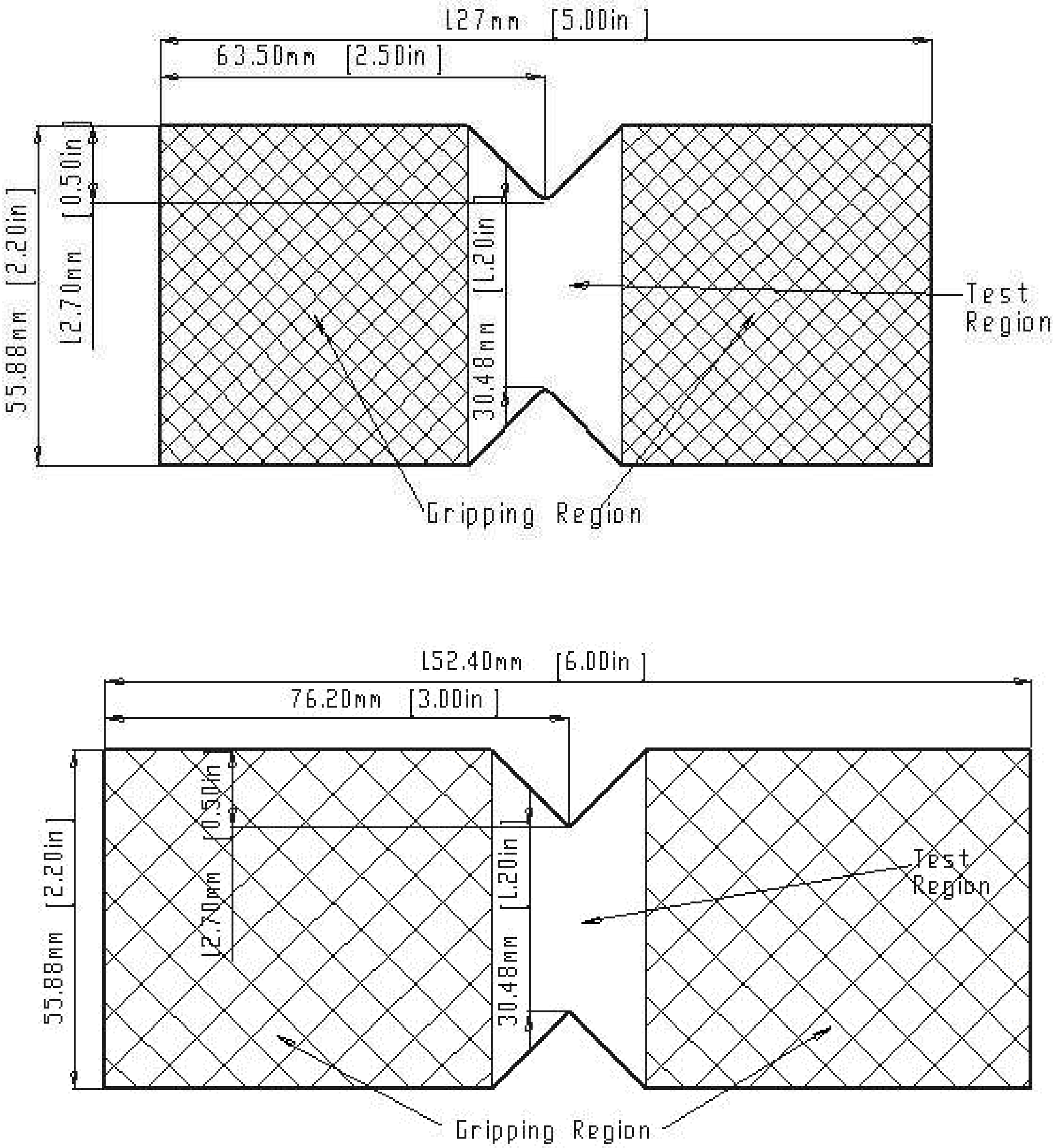


Figure 3.5 The 127 mm (5.00 in) and the 152.40 mm (6.00 in) long specimens

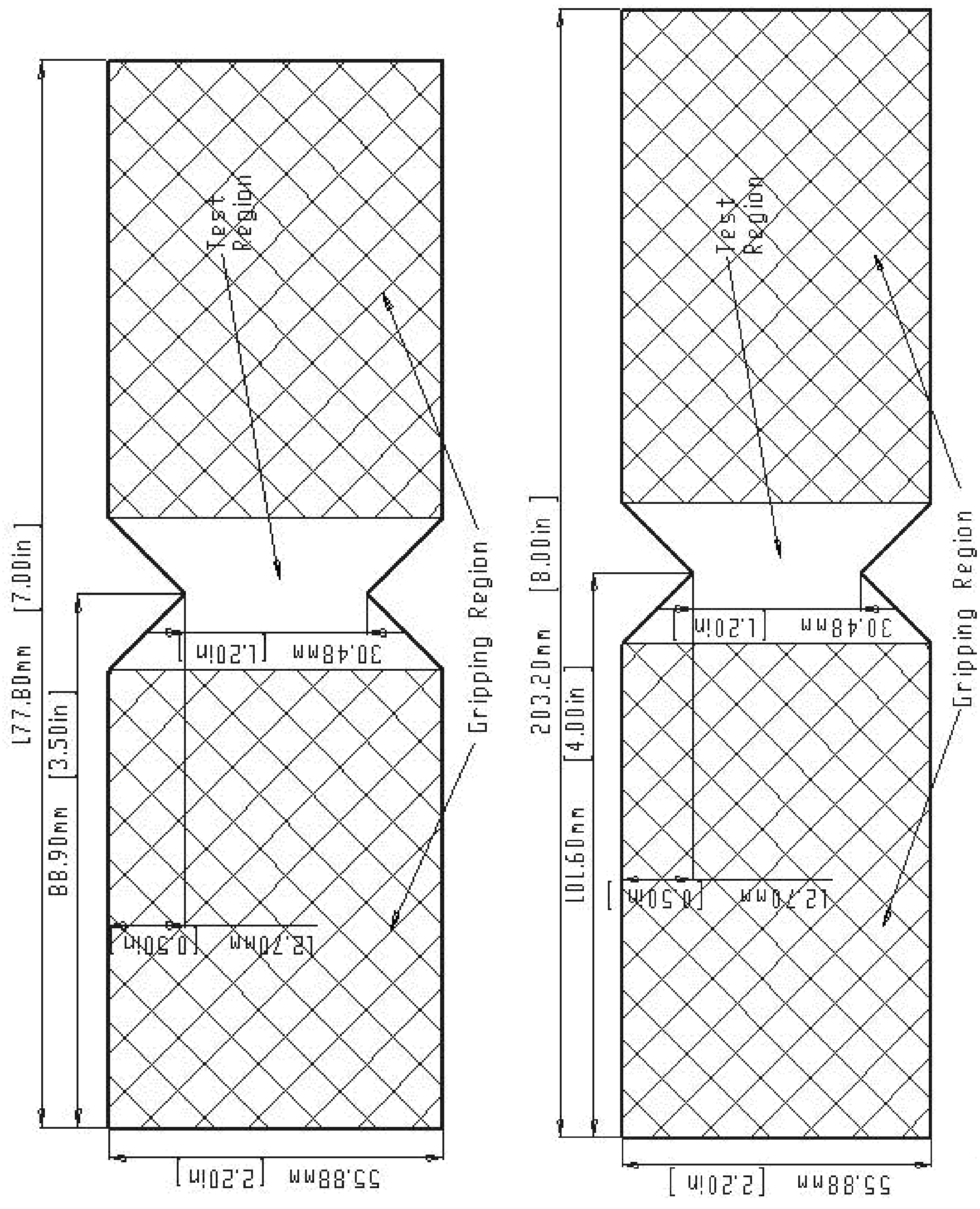


Figure 3.6 The 177.80 mm (7.00 in) and the 203.20 mm (8.00 in) long specimens

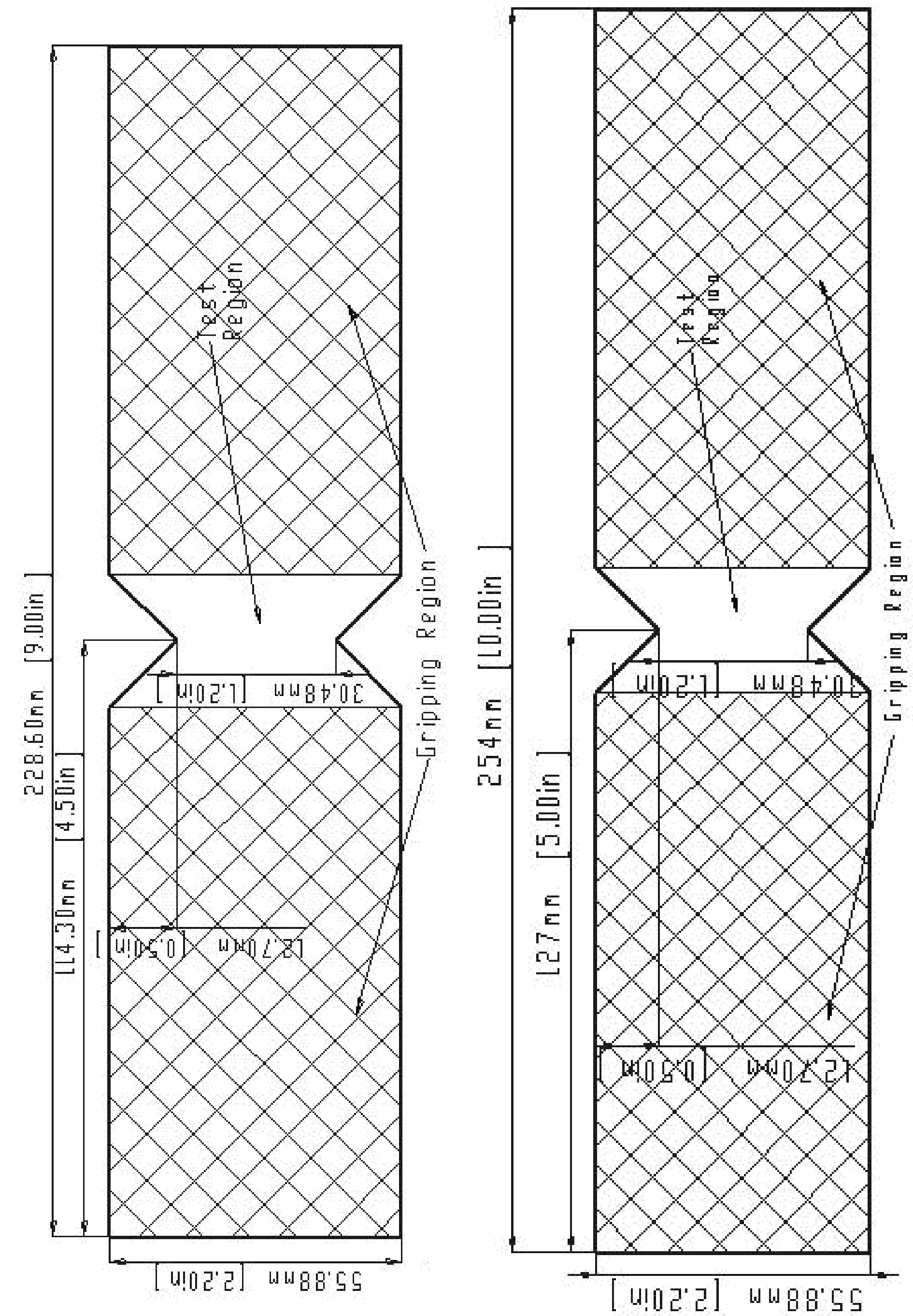


Figure 3.7 The 228.60 mm (9.00 in) and the 254 mm (10.00 in) long specimens

In order to maintain a constant gripping pressure, the gripping loads, which are applied perpendicular to the load plates, were increased proportionally as the grip area increased. Constant gripping pressure is necessary because when the frictional surface is resisting rotation instead of linear motion, then the geometry of the surface area and the pressure applied to it affect the load at which slipping occurs.

The thickness of the specimens modeled ranged from 1.27 mm (0.05in) to 6.35 mm (0.25 in). This range of thicknesses is representative of all the thicknesses tested experimentally.

3.4 Test Fixture Geometry

Three different test fixtures were modeled in this study. They were: friction-only loading grips for the grip length study, a model of the ASTM D 7078 fixture, and a fixture that applies load through friction and edge loaders too, known as the Combined Loading fixture.

The friction only fixture used in the grip length study is shown in Figure 3.8. In this figure, two frictional face loaders are shown, similar to the face loaders used in the V-Notched fixture. The vertical dimensions remained constant and are shown in the figure. The horizontal dimensions, L and D, were increased or decreased depending on the length of the specimen being tested. The fixture shown in Figure 3.8 is sized for a 76.2 mm (3.00 in) long specimen.

The friction-only fixture for the grip length study was first loaded by applying normal loads to the rectangular cavities on the backside of the loading plates. These loads are labeled “N” in Figure 3.8. The left face loader was constrained in the x and y directions while the right face loader was constrained in the x direction to prevent rotation. The backside of the specimen (not pictured) was constrained in the z direction for symmetry. A downward load was applied in the y direction on the face of the cavity of the right face loader to simulate the loading of the specimen. This load is labeled “F” in Figure 3.8.

In Figure 3.9 the model for the ASTM D 7078 (V-Notched) fixture is shown. The rails are shown in light grey and the face loaders are shown in dark grey. This fixture was used to model 76.2 mm (3.00 in) long specimens loaded by friction only in the thickness effects study. Some of the dimensions are listed in the figure. These dimensions are shown to illustrate the size of the fixture. This fixture has the same dimensions as the V-Notched rail shear fixture described in ASTM D 7078 [2]. The load plates used in the V-Notched fixture (shown in dark gray in Figure 3.9) have the same dimensions that are listed in ASTM D 7078 [2].

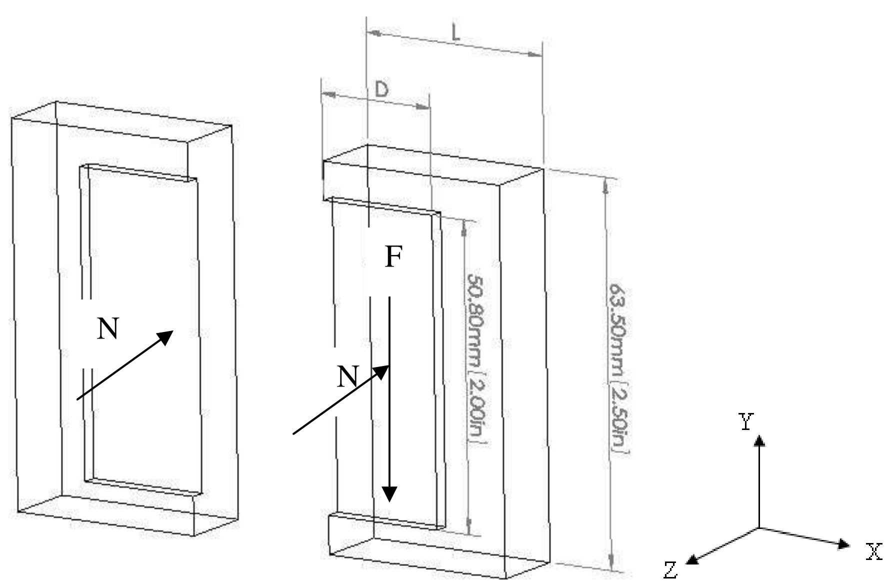


Figure 3.8 The friction-only fixture modeled for finite element grip length study

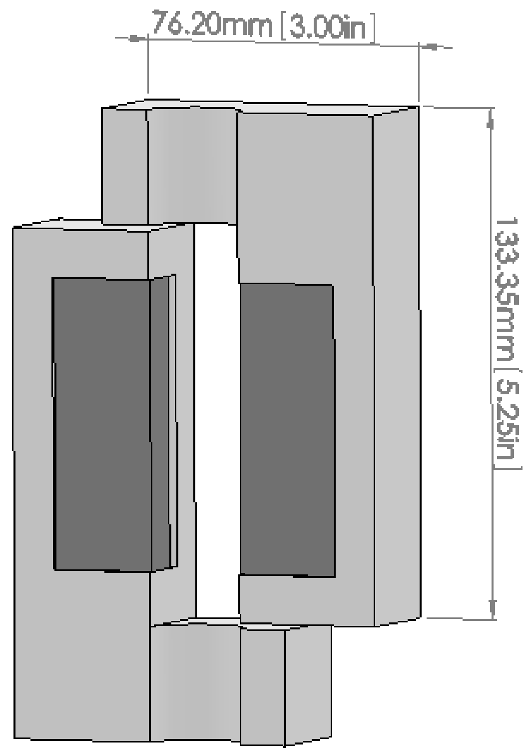


Figure 3.9 The V-notched fixture model used for the thickness effects study

Frictional contact surfaces were modeled between the specimen and the face-loaders. No-separation contact surfaces were modeled between the face loaders and the adjacent faces in the cavities of the rails. No-separation contacts act like bonded contacts but allow a small amount of slipping to occur between the surfaces. This contact condition is ideal for this contact because it allows the load to be transferred to the face loaders from the rails, and it also allows the face loaders to slide-in to apply the normal load to the gripping regions of the specimen.

The Combined Loading fixture model can be seen in Figure 3.10. This fixture was used in the laminate effects study and the thickness effects study to model 76.2 mm (3.00 in) and 127 mm (5.00 in) long specimens being loaded in the Combined Loading fixture.

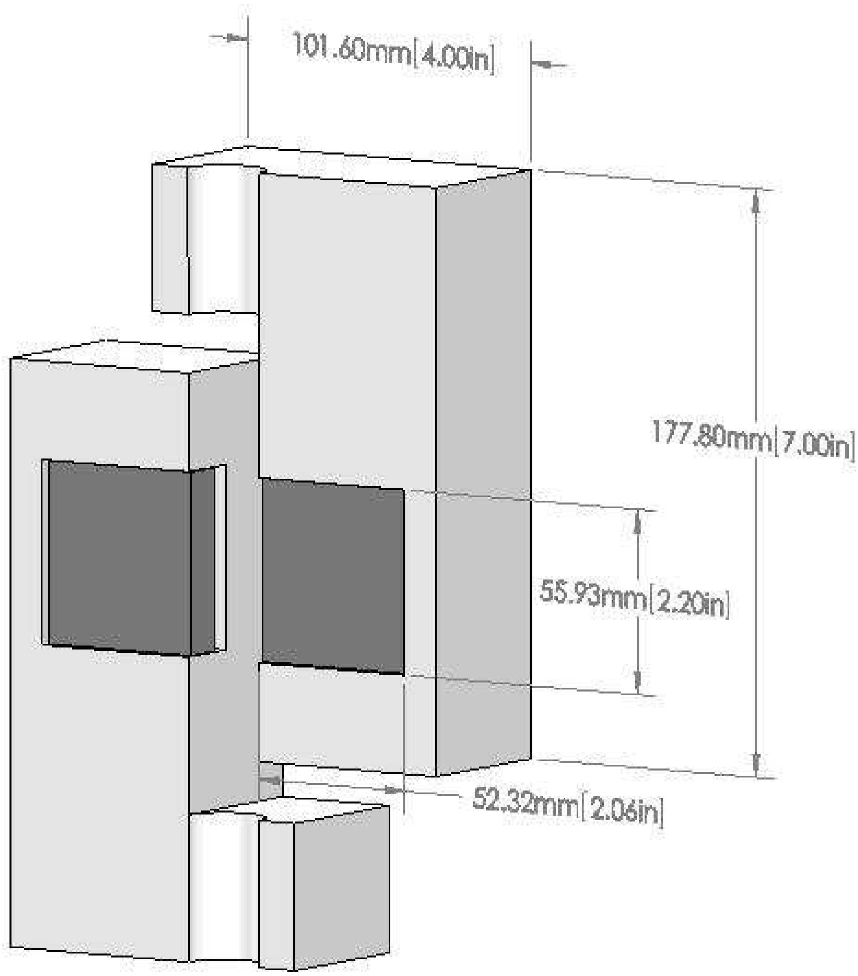


Figure 3.10 The Combined Loading fixture modeled for the thickness effects and laminate effects studies

Some of the dimensions are listed in the figure to show the size of the fixture. This fixture differs from the V-Notched fixture in that is it much larger and the cavity for the face loaders and the specimen is shaped differently. The dimensions for the face loaders used in this fixture are shown in Figure 3.11. The four holes on the back side of the face loaders are used to apply the normal forces that create the gripping pressure on the face-loader/specimen interface. The same contacts that are modeled in the V-Notched fixture

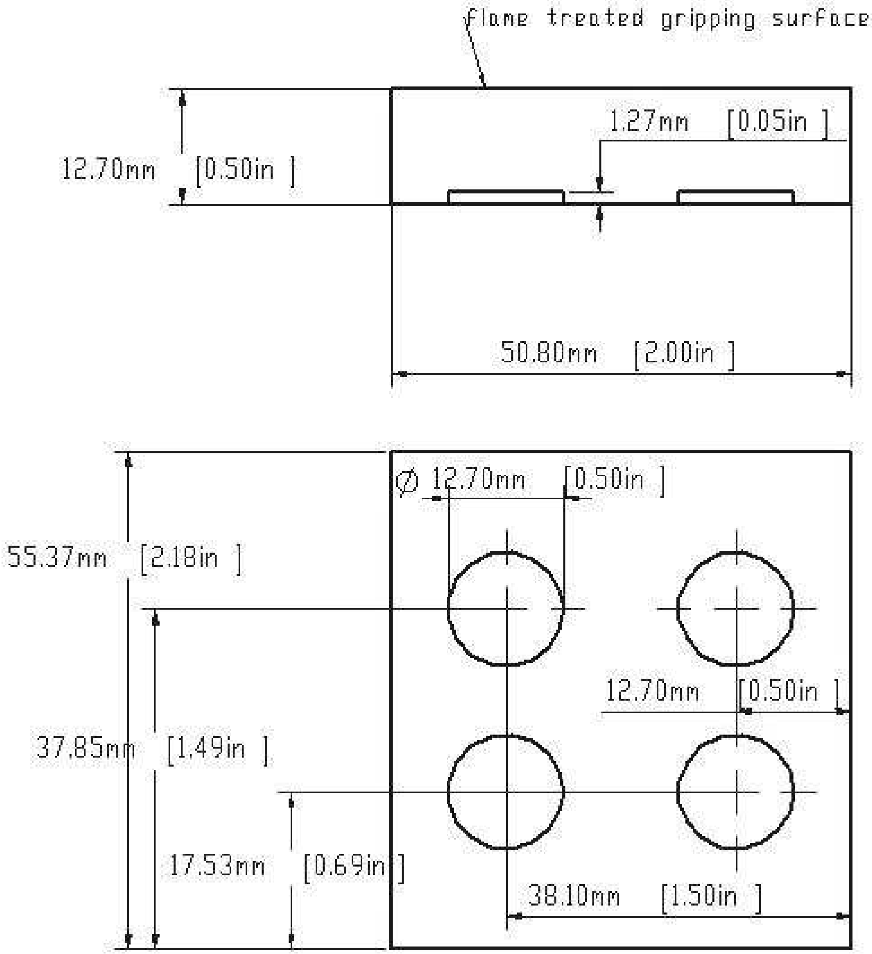


Figure 3.11 The face loader used in the Combined Loading test fixture model

model exist in this fixture's model, with the addition of one: the Combined Loading fixture has frictionless contact surfaces modeled between the top and bottom edges of the gripping region of the specimens and the adjacent surfaces in the cavities of the rails. A detailed view of an edge loader and the corresponding specimen edge are shown in Figure 3.12. The edge loader is shown with horizontal lines filling the surface. The specimen edge is shaded in grey. This additional contact surface models the edge-loading that was used in the new Combined Loading fixture.

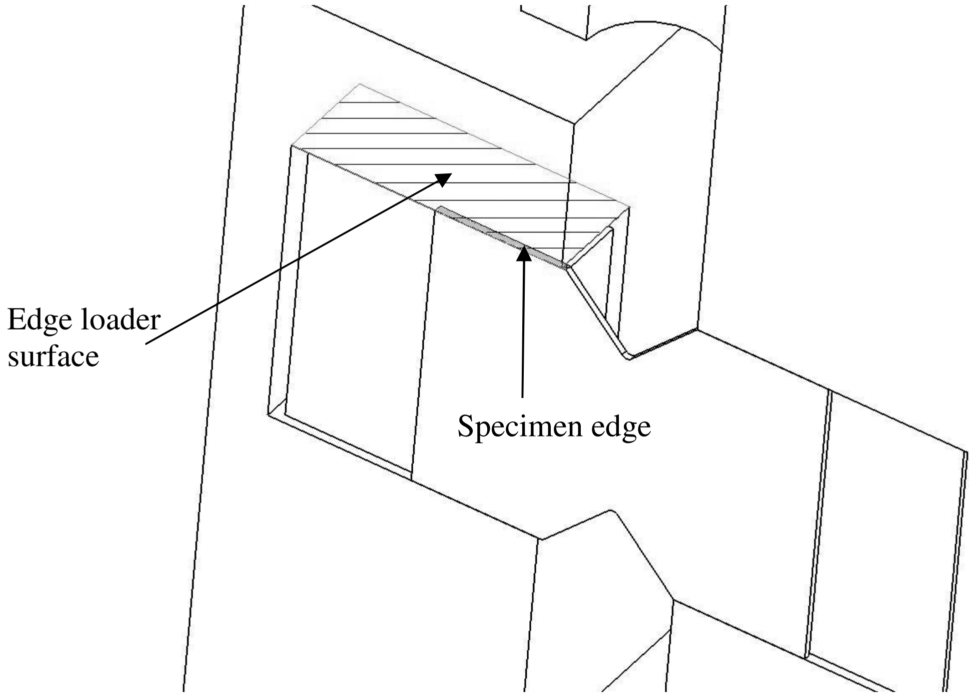


Figure 3.12 A detailed view of the edge loader and the specimen edge it contacts

3.5 Mesh Refinement

The test regions in the specimens experience large stress gradients, and require finer meshes than the mesh shown in Figure 3.1. Mesh refinement in ANSYS Workbench can be accomplished using three different methods. The first is to change the resolution of the whole model. This process would result in high resolution throughout the whole model, and greatly increase the time required for the model to converge while minimally improving accuracy. The other two methods use the Body Sizing function. The Body Sizing function can increase the resolution of an individual part or it can focus the increased resolution to a specific area using what ANSYS refers to as “Sphere of Influence.”

A Sphere of Influence is a sphere in the model in which the size of the elements is designated by the user instead of being automatically determined by the computer program. The use of the Sphere of Influence allows the modeler to refine the mesh only where refinement is determined necessary. For this reason, Spheres of Influence were used to refine the meshes in this study.

A sphere of influence can be seen in Figure 3.13. In this figure, one of the spheres of influence can be seen centered at the top notch of the specimen. It has a radius of 12.7 mm (0.5 in). An identical sphere of influence was placed at the bottom notch as well. Some of the meshes that resulted from using different element sizes can be seen in Figure 3.14. In this figure, the element sizes specified are 2.54 mm (0.1 in), 2.03 mm (0.08 in), 1.52 mm (0.06 in), and 1.27 mm (0.05 in). It can be seen in these pictures that the refinement of the mesh is only taking place inside the spheres of influence.

The different element sizes that were investigated through this mesh refinement ranged from 0.76 mm (0.03 in) up to 3.56 mm (0.14 in). The results that were investigated as evidence of convergence were the maximum displacement of the model and the maximum shear stress. Table 3.2 shows the results from the mesh refinement. The reason that the maximum displacement was investigated is because it is generally a good indicator as to the convergence of the finite element model. As it can be seen in Figure 3.15, the plot of the maximum displacement vs. the inverse of the element size, there is not a discernable trend for the maximum displacement in relation to element size. This is believed to be due to the fact that much of the displacement that is taking place is due to the slipping of the specimen in relation to the load plates. Since the slipping makes this model a non- linear problem, it should not be expected that the maximum

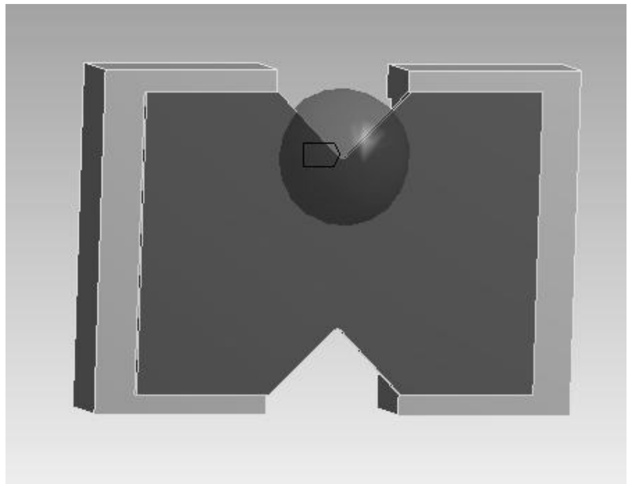
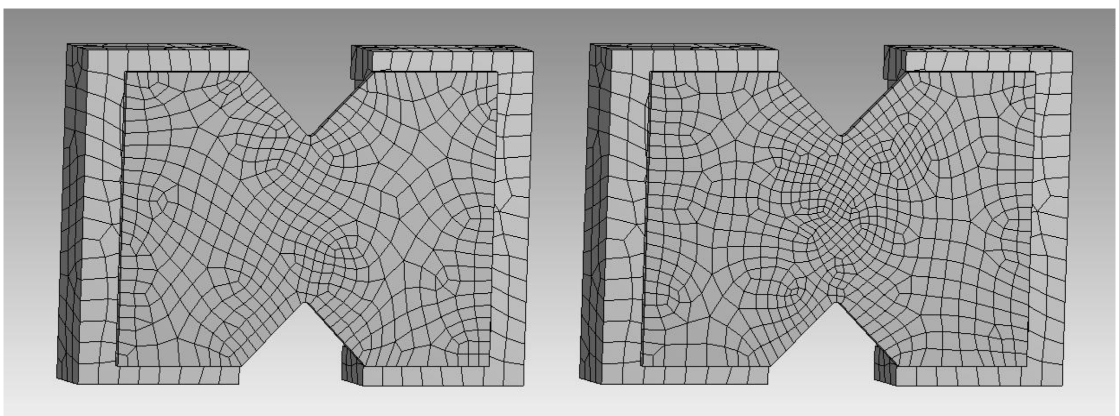
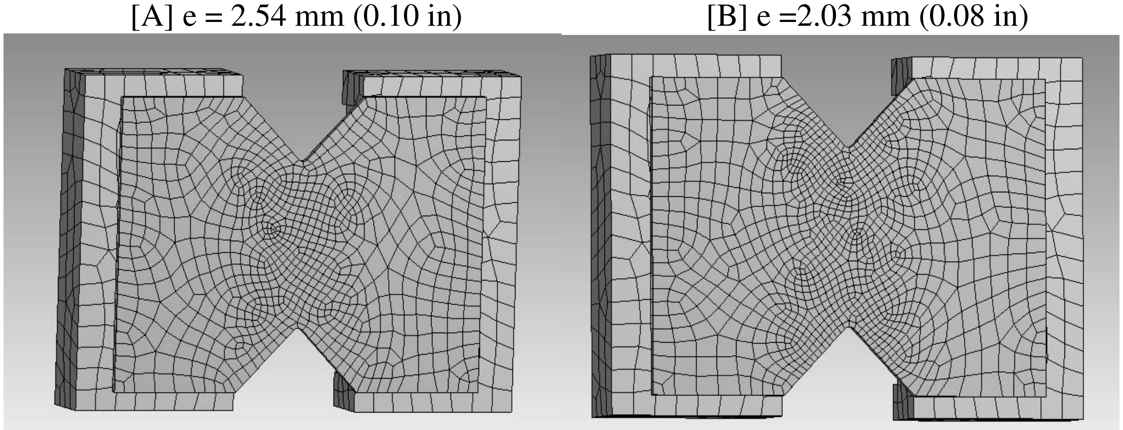


Figure 3.13 A Sphere of Influence



[A] e = 2.54 mm (0.10 in) [B] e =2.03 mm (0.08 in)



[C] e = 1.52 mm (0.06 in) [D] e = 1.27 mm (0.05 in)

Figure 3.14 Different element sizes are specified in the spheres of influence

Table 3.2

Results from the mesh refinement

1/Element Size, 1/mm	Max Displacement, mm (in)		Max Shear Stress, MPa (ksi)		Normalized Max Shear Stress
0.28	2.00	(0.08)	647.51	(93.914)	1.295
0.33	1.91	(0.07)	766.63	(111.19)	1.533
0.39	1.86	(0.07)	710.23	(103.01)	1.420
0.49	1.91	(0.07)	702.23	(101.85)	1.404
0.66	1.93	(0.07)	824.27	(119.55)	1.649
0.79	2.03	(0.08)	823.17	(119.39)	1.646
0.98	2.01	(0.08)	891.15	(129.25)	1.782
1.31	1.84	(0.07)	892.73	(129.48)	1.785

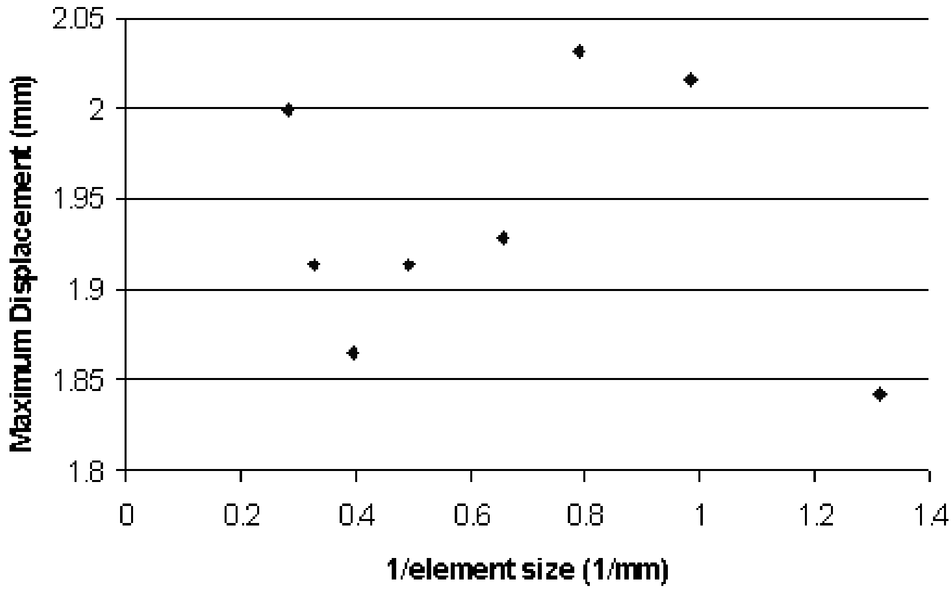


Figure 3.15 The maximum displacement vs. the inverse of the element size

displacement would act as a good indicator for convergence. Also, all of the mesh refinement is taking place away from the gripping surfaces where the slipping is occurring and so it would not affect the slipping.

The maximum in-plane shear stress (τ_{xy}) was investigated as an indicator of convergence because it is the stress that is of most interest to this study. This stress was recorded near the tip of the top notch of the specimen. In Table 3.2, the last column is labeled the normalized maximum shear stress ($\tau_{xy,norm}$). This value is calculated by dividing the maximum shear stress ($\tau_{xy,max}$) by the average shear stress ($\tau_{xy,ave}$) across the gage section. The average shear stress is the force applied on the model (labeled "P" in Figure 3.1) divided by the minimum cross-sectional area. The cross-sectional area is calculated as the thickness of the specimen multiplied by the distance between the notches. The equations for calculating the normalized maximum shear stress, the average shear stress, and the minimum cross-sectional area are shown in equation 3.1.

$$\tau_{xy,norm} = {\tau_{xy,\max}}/{\tau_{xy,ave}} \qquad (3.1)$$
$$\tau_{xy,ave} = {F}/{t*d}$$

Figure 3.16 is a plot of the maximum in-plane shear stress ($\tau_{xy\ norm}$) vs. the inverse of the size of the elements. These results appear to be approaching 1.8 asymptotically. A curve fit is placed over these results (shown as the solid line in the figure). From the fit of the data shown in Figure 3.16, it appears that having the element size set at 1.02 mm (0.04 in), (1/element size = 0.98 mm^{-1}) will achieve nearly the same results as having the element size set to 0.76 mm (0.03 in). It was decided that with the element size set to 1.02 mm, the mesh is adequately refined.

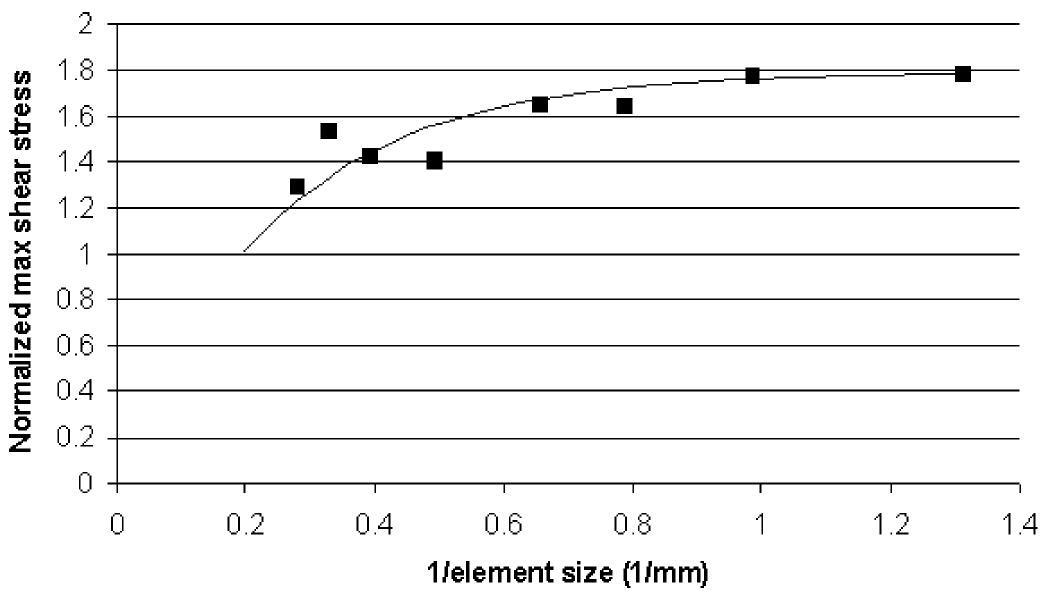


Figure 3.16 Normalized max shear stress ($\tau_{xy\ norm}$) vs. 1/element size.

4. FINITE ELEMENT RESULTS

4.1 Introduction

The goal of the finite element modeling was to determine what modifications would be most effective in increasing the load capacity of the V-Notched Rail Shear test method. The two methods for improvement that were studied were the lengthening of the gripping regions, and the addition of edge loaders. In order to know whether or not the modifications were effective, it is important to understand the limitations of the current V-Notched Rail Shear test. Friction tests done for this study show that the existing test fixture is adequate for testing specimens that fail below 53 kN (12 kip). When loads exceed 53 kN (12 kip), the ability of the fixture to adequately restrain the specimen comes into question. When the specimen is not adequately restrained then it will rotate within the fixture.

To prevent the specimens from rotating in the grips and in order to facilitate the testing of specimens above 53 kN (12 kip), two modifications to the V-Notched Rail Shear test method were investigated. The first is the lengthening of the gripping regions. The second modification is the addition of edge loaders similar to those used in the Iosipescu fixture [1]. The addition of edge loaders would provide normal forces to the edges of the specimens when they are beginning to slip and prevent the slipping from occurring. The addition of edge loaders to the V-Notched fixture is known as Combined

Loading. These two modifications were investigated separately and together to determine their effectiveness in preventing slipping.

The most effective way to determine if the modifications are effective is to determine whether they are preventing large rigid-body motion of the specimen, i.e. slipping, in the finite element models. It is also important that any modifications done on the shear test do not adversely affect the state of stress in the specimens. In previous work done [5] on the V-Notched Rail Shear test method, it was shown that the in-plane shear stress throughout the gage section was highly uniform, and that the normal stresses were negligible. For this reason, the in-plane stresses, σ_x, σ_y, and τ_{xy} were analyzed on all the modifications that were investigated to verify that the state of stress in the modifications is as uniform as it is in the existing shear test.

Although previous research [5] on this shear test showed the state of stress is highly uniform and effective for shear testing, all the modeling was done on one thickness. None of the modeling done in the previous research for the V-Notched Rail Shear test method [5] analyzed the effects the thickness of the specimen has on the state of stress. Being that the specimens in the existing shear test are only loaded through the faces, it could be that for very thick specimens that the shear stresses will be concentrated near the surface while the interior has lower shear stresses. For this reason, the state of shear stress through the thickness was investigated for the existing shear test and all modifications.

During preliminary modeling, a study was done to determine the coefficient of friction between the face loaders and the specimen faces. This study was necessary so a valid coefficient of friction could be used for all subsequent models.

4.2 Data Processing

The results that follow were created by modeling in ANSYS Workbench [6], then importing the nodal results into Microsoft Excel [7] for data manipulation, and then importing the Excel data into Surfer 7.0 [8], a contour plotting software to generate plots. In the contour plots of stress, all to the stresses are divided by the average shear stress across the gage section. This means that a favorable state of stress in a plot would show a value of 1.0 across the gage section for the in-plane shear stress and a value of 0.0 for σ_x, σ_y, and σ_z in the gage section.

4.3 Preliminary Modeling

Prior to this study, no research was found on the slipping that occurs in the gripping region of the V-Notched Rail Shear fixture when the specimen is stronger than the gripping force applied by the face loaders. There was no data as to what the coefficient of friction might be for specimen/face-loader interface. For this reason, a study was conducted to determine what the coefficient of friction is. This study had two separate parts. The first was the mechanical testing done to determine the load at which specimens slip for a given bolt torque. The second was the computational modeling performed to determine what the corresponding coefficients of friction would be for the specimens to slip at the loads determined experimentally. The first part will be discussed in detail in the Experimental Results chapter, Chapter 6. The second part will be discussed here.

In order to model this friction experiment, it is necessary to know what force the allen head bolts in the test fixture are applying to the specimen. Equation 8-5 from

Shigley's Mechanical Engineering Design, Eighth Edition [9] has all the terms necessary to find the force applied. The equation is the following:

$$T_R = \frac{Fd_m}{2}\left(\frac{l + \pi f d_m \sec(\alpha)}{\pi d_m - fl \sec(\alpha)}\right) \tag{4.1}$$

where T_R is the Torque required to turn the bolt, F is the force applied by the screw on the load plate, l is the distance between threads, d_m is the mean diameter of the screw, f is the coefficient of friction between the screw and the material it is threaded into, and α is half of the thread angle. A diagram of a bolt with all of these dimensions is shown in Figure 4.1. The screws used by the V-Notched Rail Shear fixture to apply the normal load onto the specimen are ½-20 inch, meaning that the diameter is a half-inch, and there are 20 threads per inch. This being the case, the constants in equation 4.1 are the shown in Table 4.1.

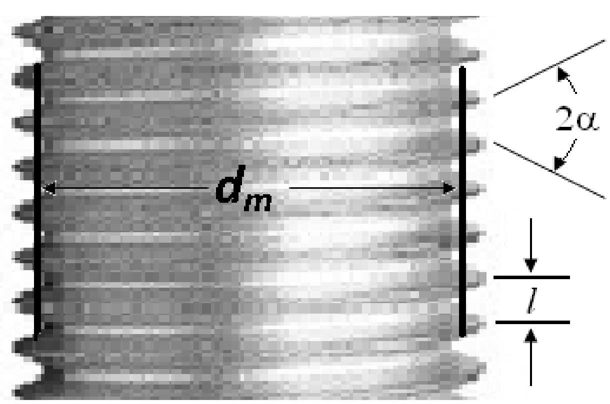


Figure 4.1 The dimensions for equation 4.1

Table 4.1

Constants for equation 4.1

d_m	12.13 mm (0.4775 in)
l	1.27 mm (1/20 in)
α	30º
f	0.15

The coefficient of friction is given in *Shigley's Mechanical Engineering Design, Eighth Edition*, page 408, Table 8-5 [9]. Using these values for the constants, equation 4.2 reduces to the following:

$$F = 793.7 * \frac{1}{m} * T_R \tag{4.2}$$

where F is in Newtons and T_R is in Newton-meters. ASTM D 7078 suggests a torque value of 55 N-m (40.6 ft-lb) for the bolt, but also states that the torque required is dependent on the material being tested. For this reason, the torque values tested experimentally for this friction study were 45 N-m (33 ft-lb), 55 N-m (40 ft-lb), and 65 N-m (48 ft-lb). Using equation 4.2, the forces applied to the gripping plates were determined. These forces are shown in Figure 3.8 The friction-only fixture modeled for finite element grip length study as the Total Normal Force, and are the total normal forces used in the finite element model. These forces are labeled "N" in Figure 3.8.

Table 4.2 also shows the average load at which the experimental specimens began slipping. These values were determined experimentally and were used in ANSYS as the downward load on the specimen in the finite element model. This load is labeled in Figure 3.8 as force F, and is only half of the load determined experimentally to cause slipping because the model is taking advantage of symmetry. Through multiple iterations, the coefficients of friction that would cause the specimens to start slipping at the loads listed in Table 4.2 were determined. It was determined that these were the correct coefficients of friction because the finite element model predicted that the specimens would not slip with higher coefficients of friction, and that they would slip prematurely with a lower coefficients of friction. The coefficients of friction (COF) for each of the torque values are shown in Table 4.2 along with the average coefficient of friction for all the torque values. The average coefficient of friction value shown in Table 4.2 was then used in all of the following finite element modeling.

Figure 4.2 is a vector plot of the nodal displacements from the finite element solution to the friction study. The arrows shown in this plot are vectors for the total displacement of the nodes in the model. The direction of the arrow shows the direction that the node has moved in and the length of the arrow and the color of the arrow illustrate the magnitude of the displacement. From this figure, it can be seen that the finite element model predicts that the specimen will rotate around a point located midway up the height of the specimen and near the right edge.

4.4 Specimen Length Effects

It is proposed that increasing the length of the grip region, while maintaining the dimensions of the test region as they are prescribed in ASTM D 7078 [2], could prevent the specimens from slipping in the grips. The different length specimens presented in the previous chapter were modeled using ANSYS Workbench. Increasing loads were placed on the models until the computer was not able to return results due to large rigid body

Table 4.2

Finite element friction results

Torque: (N*m)	45	55	65
Total Normal Force, N	107157.5	130970.3	154783.1
(lb)	(24091.2)	(29444.8)	(34798.4)
Experimental Average Slipping Load, N	35200.0	40761.4	47297.1
(lb)	(7913.7)	(9164.0)	(10633.4)
Corresponding COF:	0.295	0.28	0.275
Average COF:		0.2833	

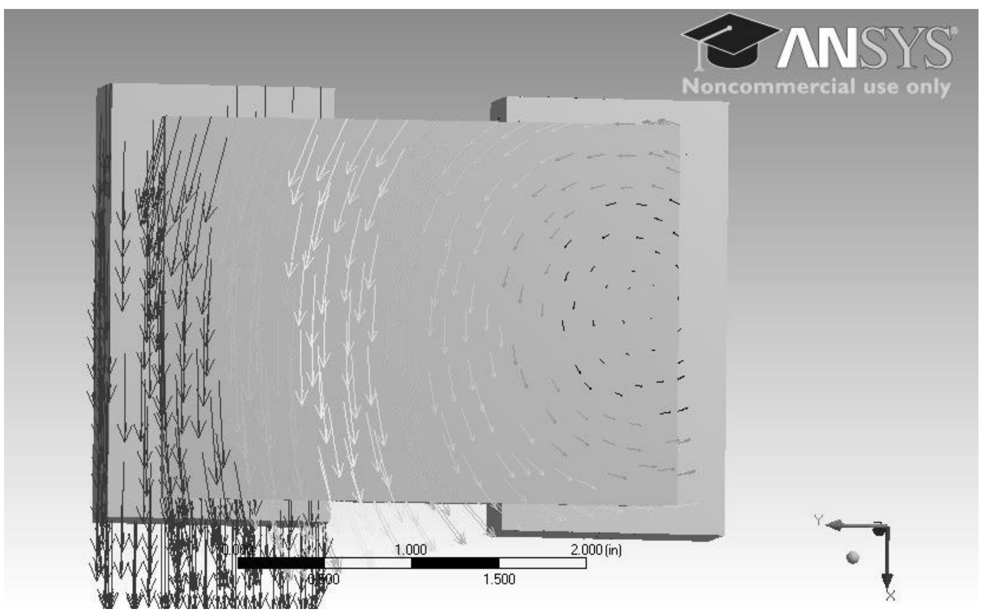


Figure 4.2 A vector plot of the total deflection of the finite element friction analysis

motion. The highest loads that the finite element models predicted that the specimens were able to resist slipping are shown in Table 4.3.

From the results of the specimen length study, it can be seen that by increasing the length of the specimen, the maximum force at which the finite element model predicts slipping appears to increase linearly. While increasing the length of the specimen may be effective, it is advantageous to maintain a shorter specimen. The advantages to maintaining a smaller specimen include a reduction in the amount of material needed to create specimens, and larger specimens would require a much larger test fixture. Putting the large specimens into large fixtures, and placing those fixtures into a test frame becomes a daunting task for any person. For this reason, it is of some interest that the specimen length does not increase immensely, and that further investigations are done into the possibility of securing the specimens in other ways so that they do not slip.

4.4.1 Combined Loading Modification

It is proposed that if the top and bottom edges of the specimens were secured, then the specimens would not rotate and the same uniform state of shear that exists in the current V-Notched Rail Shear test would be present. The securing of the edges is proposed to be done by adding edge loading devices (similar to those used in the Iosipescu fixture) to a V-Notched Rail Shear Fixture. Figure 4.3 shows a Solidworks model of the prototype with one side removed to illustrate how the surface and edge loads are applied to the specimen. The face loading plates in the prototype differ from those in the original V-Notched fixture in that they are slightly smaller than the specimen in height (they are 55.37 mm (2.18 in) while specimens are 55.88 mm (2.2 in)). This is

Table 4.3

Results from the load-to-cause-slipping finite element study

Specimen Length, mm (in)		Grip Length, mm (in)		Predicted Slipping Load, N (lb)	
50.8	(2.00)	12.7	(0.50)	11231	(2525)
63.5	(2.50)	19.1	(0.75)	16013	(3600)
76.2	(3.00)	25.4	(1.00)	20376	(4581)
101.6	(4.00)	38.1	(1.50)	27355	(6150)
127	(5.00)	50.8	(2.00)	34694	(7800)
152.4	(6.00)	63.5	(2.50)	41366	(9300)
177.8	(7.00)	76.2	(3.00)	47594	(10700)
203.2	(8.00)	88.9	(3.50)	53376	(12000)
228.6	(9.00)	101.6	(4.00)	60048	(13500)
254	(10.00)	114.3	(4.50)	66720	(15000)

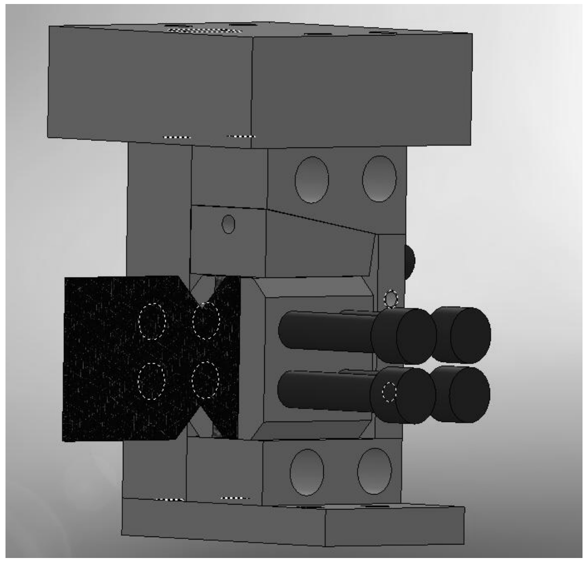


Figure 4.3 A Solidworks model of the Combined Loading prototype

done to facilitate the edge loading of the specimen. It can also be seen in Figure 4.3 that the edge loading is similar to the edge loading in the Iosipescu fixture. A bolt on the back of the fixture at a 10-degree angle moves the top edge loading block in and down to clamp down on specimens.

This new method of introducing load into the specimen is known as the Combined Loading Modification of the V-Notched Rail Shear test. The finite element model of this fixture has been explained in Section 3.4 in the previous chapter.

It was decided that the Combined Loading Fixture would be designed so that it would be able to test specimens up 127 mm (5.00 in) in length. This length of specimen was decided upon because the increased length would improve the gripping on the face loaders and fixture would not have to be so large that it would be difficult to load it into the load frame.

The specimens measuring 127 mm (5.00 in) and 76.2 mm (3.00 in) long were modeled in the Combined Loading test fixture. The 76.2 mm (3.00 in) long specimens were modeled in the Combined Loading fixture so that the effects of Combined Loading without an increased gripping region could be investigated.

4.5 Slipping Results

To determine the effectiveness of the Combined Loading fixture, the amount of slipping that occurs for each test method (ASTM D 7078 and Combined Loading with 76.2 mm (3.00 in) and 127 mm (5.00 in) long specimens) for a given load will be shown. The following plots were made in Surfer 7.0 [8]. Figure 4.4, Figure 4.5, and Figure 4.6 are contour plots of the slipping between the face-loaders and the specimens. The slipping that occurs is measured as the difference in the magnitude of the deflection of the nodes on the surface of the face-loaders and the nodes on the face of the specimens, measured in millimeters. All the models had a 20016 N (4500 lb) load applied to them.

In each of these plots the surfaces shown are the roughened, gripping surfaces of the face-loaders that are in contact with the gripping regions of the specimens. In all of these figures, the left sides of the face loaders are near the test region of the specimens and the right sides are near the ends of the specimens. From these results, it can be seen that a majority of the slipping in all of the specimens occurs near the corners of the face-loaders that are next to the test region of the specimen.

4.5.1 ASTM D 7078 Slipping Results

Figure 4.4 is the nodal slipping results for the face loader in the current shear test, ASTM D 7078. In Figure 4.4, it can be seen that when a 20016 N (4500 lb) load is applied to the model (which would be the same as a 40032 N (9000 lb) load applied to an experimental specimen), the largest amount of slipping has a magnitude of 0.75 mm

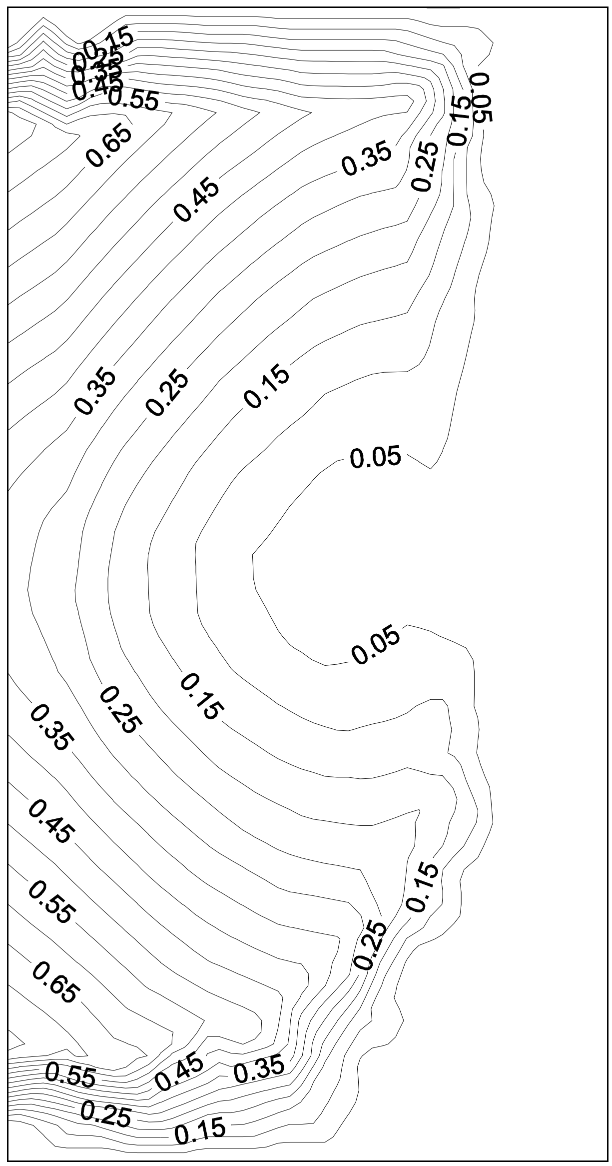


Figure 4.4 Contour plot of the slipping for ASTM D 7078 model

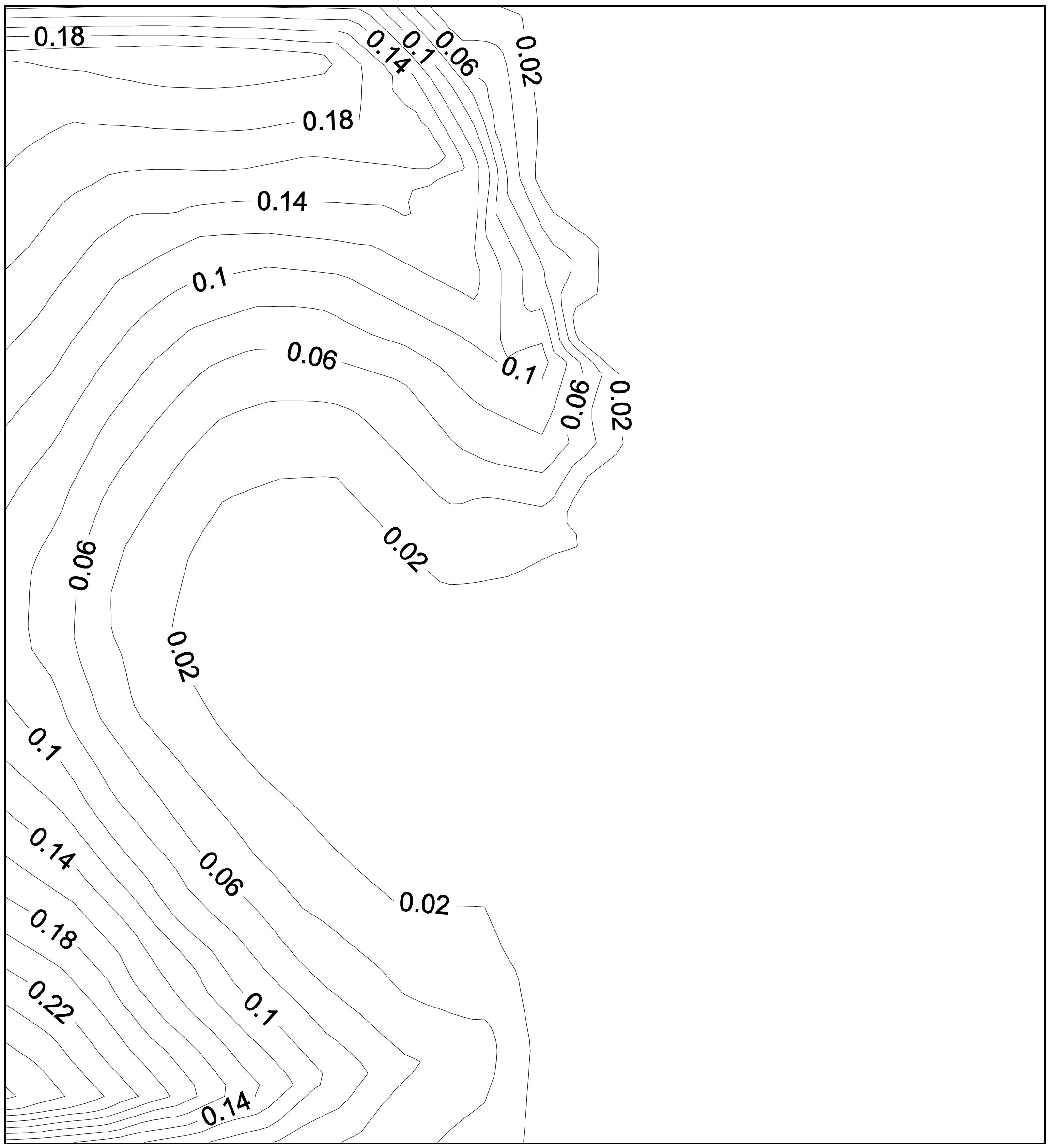


Figure 4.5 Contour plot of the slipping for 76.2 mm (3.00 in) Combined Loading model

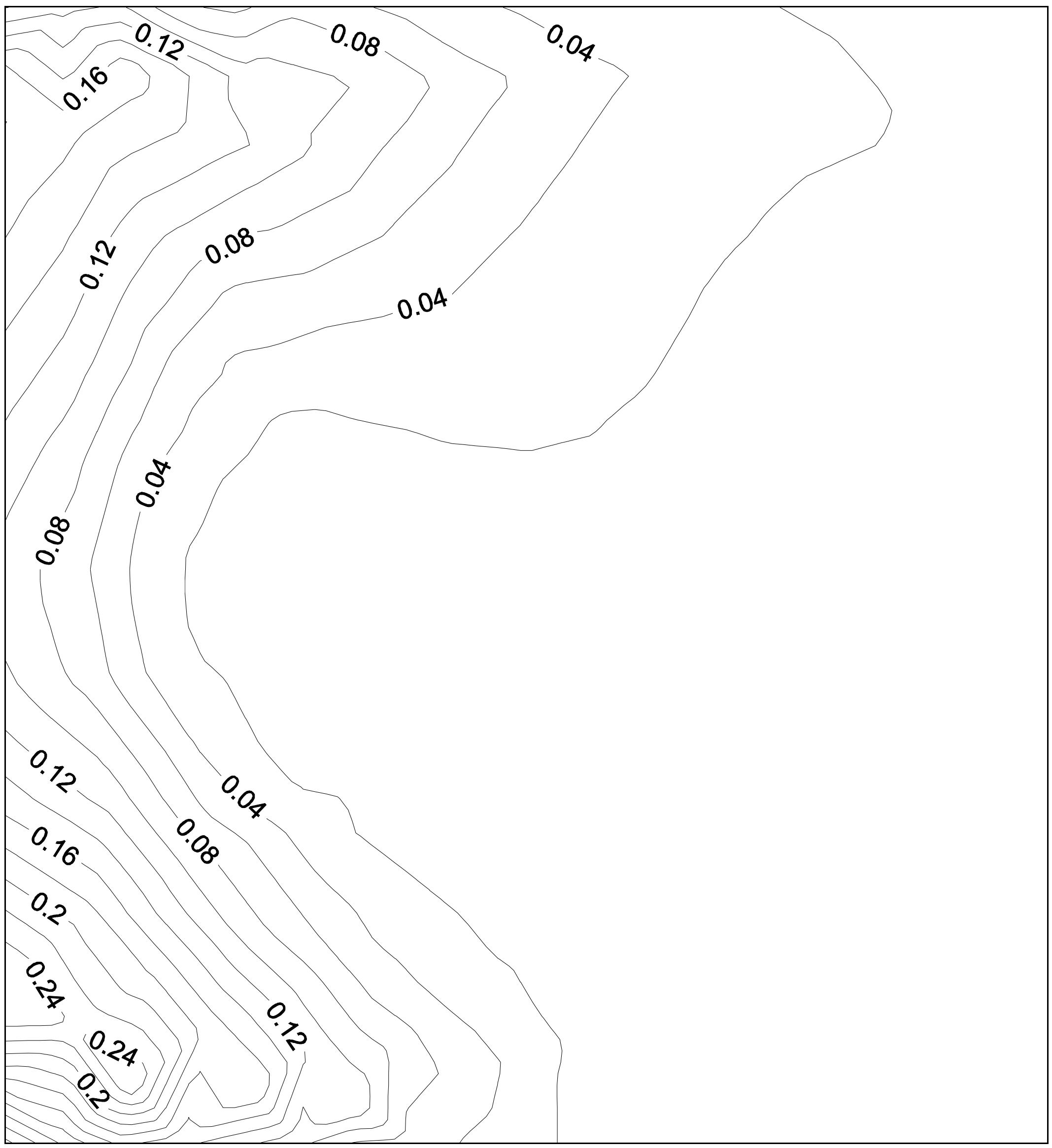


Figure 4.6 Contour plot of the slipping for 127 mm (5.00 in) Combined Loading model

(0.0295 in).This slipping occurs near the top and bottom corners on the left side, which is next to the specimen test section.

4.5.2 Slipping Results of a Combined Loading 76.2 mm (3.00 in) Long Specimen

Figure 4.5 is a plot of the predicted slipping that will occur for a 76.2 mm (3.00 in) long specimen tested in the Combined Loading fixture. These results show the largest amount of slipping to be 0.28 mm (0.0110 in). The most slipping occurs in the same location as it did in the ASTM D 7078 model, near the top and bottom left corners.

4.5.3 Slipping Results of a Combined Loading 127 mm (5.00 in) Long Specimen

Figure 4.6 is a plot of the predicted slipping that will occur for a 127 mm (5.00 in) long specimen tested in the Combined Loading fixture. These results show the maximum slipping to be 0.24 mm (0.0094 in). The largest amount of slipping occurs in the same location for this model that it did in the previous models, near the left corners.

From these results it can deduced that of these three options, the 127 mm (5.00 in) long specimen tested in the Combined Loading fixture will exhibit the least amount of slipping. The 76.2 mm (3.00 in) long specimen tested in the Combined Loading fixture exhibits slightly more slipping than the 127 mm (5.00 in) long specimen, and the 76.2 (3.00 in) long specimen tested in the current shear test fixture would experience considerably more slipping.

The fact that the most slipping occurs at the top and bottom corners that are next to the test region comes as no surprise. This is what was expected because it was seen in the vector plot shown in Figure 4.2.

4.6 Bolt Placement

When this research was initially started, it was believed that the placement of the bolts would be of little consequence due to the fact that the load was being applied to the load plates which are made of 12.7 mm (0.50 in) thick steel. It was the originally assumed that the localized stresses that can be expected on top side of the load plate would be distributed evenly across the surface of the bottom side of the load plate where it makes contact with the specimen. Further analysis revealed that this is not the case. A finite element analysis was conducted on a face loader for the Combined Loading fixture that was loaded in the same way that a real load plate is loaded. The boundary condition on the bottom side of the specimen was set to support compressive loads only, while equal forces were applied to the four bolt holes on the top side. Results from this analysis showed that σ_z (the stress in the direction of the loading) was highly localized on the gripping surface of the face loader. The results were exported to a text file and were then further manipulated using Excel. The σ_z values were normalized by dividing them by the average normal stress in the z-direction, $\sigma_{z,ave}$. This average stress in the z-direction was determined by dividing the total force applied to the face loader by the surface area.

After σ_z was normalized, the results were imported into the graphing program Surfer. Figure 4.7 shows the normalized σ_z on the gripping side of the load plate. As it can be seen in Figure 4.7, the stresses are highly localized on the face opposite of where the loads are applied by the bolts.

The highly localized state of stress shown in Figure 4.7 is actually quite the opposite of what is desirable. In Figure 4.7, the magnitudes of the stresses are high near the center (shown as negative due to the fact that they are compressive) and low at the

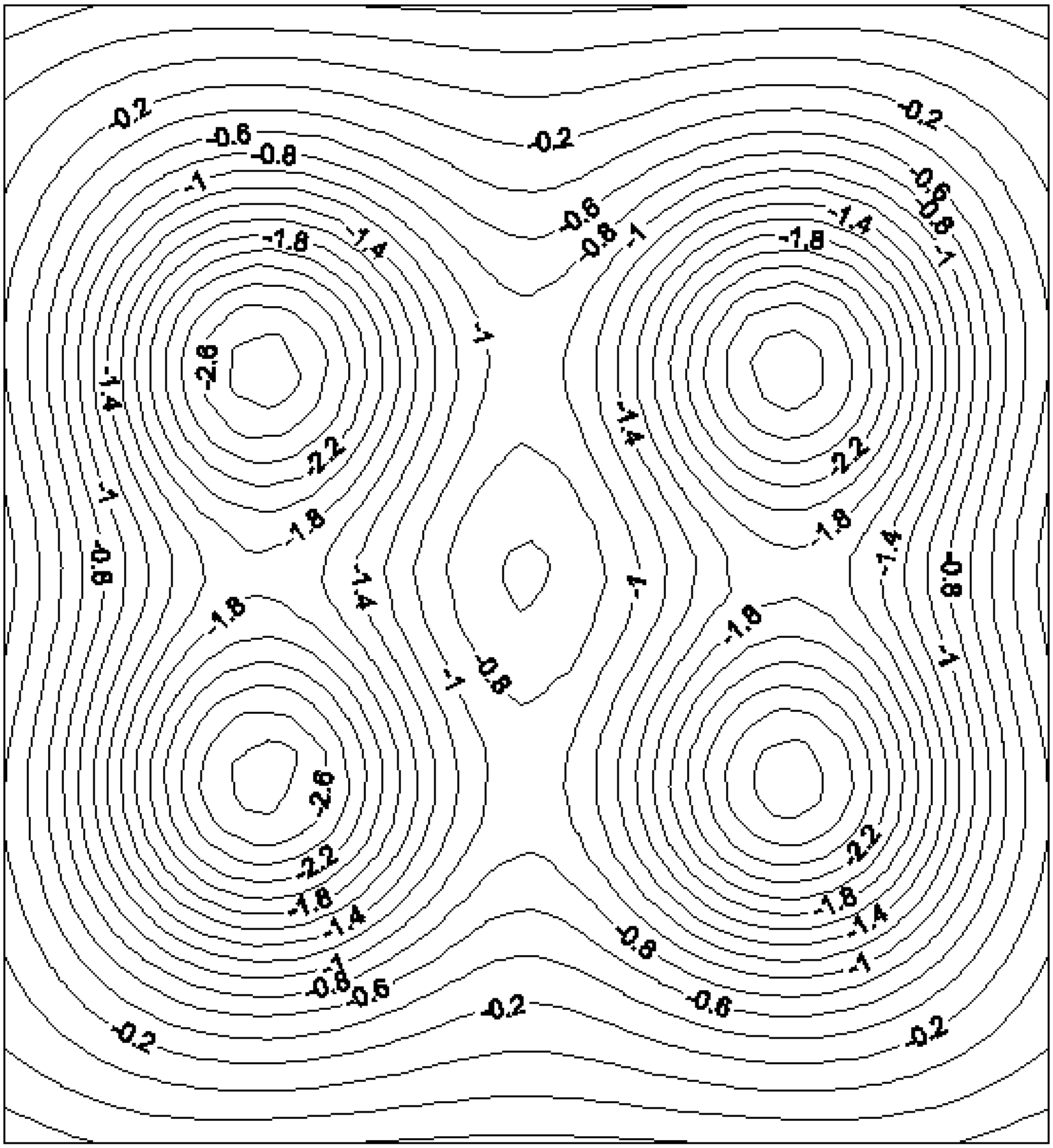


Figure 4.7 The normalized σ_z on the load face of the face loader

edges. Looking back at Figure 4.4, Figure 4.5, and Figure 4.6 will serve as reminders that the greatest amounts of slipping occur near the top and bottom edges. More specifically, slipping initiates at the top and bottom of the specimen where the gripping section is closest to the gage section. It stands to reason that the highest compressive σ_z stresses should be on the part of the specimen that is most prone to slipping (near the gage section at the top and the bottom). But instead, the compressive stresses are minima at these locations.

4.7 Laminate Effects

A comprehensive analysis of the state of stress for the existing shear test has been performed using the finite element method on various laminates and can be seen in previous work [5]. In this study, the finite element results of the laminate effects for 76.2 mm (3.00 in) long and 127 mm (5.00 in) long specimens tested in the Combined Loading fixture are shown. The laminates that were investigated are $[0/90]_{2s}$, $[0/\pm45/90]_s$, and $[\pm45]_{2s}$. The material properties of these laminates are listed in Table 3.1. All of the results shown are for models that were loaded to 11120 N (2500 lb). All the plots shown in this section are the normalized nodal stresses on the faces of the specimens. These plots are normalized by dividing them by the average in-plane shear stress at the smallest cross-sectional area, from notch to notch. In each of these plots, the difference between each contour line is 0.075 kPa/kPa.

The modeling done in this research differs from the modeling done in previous research in that the specimens were modeled in the previous research were modeled as bonded to the surface of the fixtures [5], while in this study, contact elements were employed to model the frictional loading and the edge loading used in the existing test fixture and the Combined Loading fixture.

For this study, a sign convention is used with the specimen oriented in the x-y plane. The loading direction, or y direction, for the specimen is referred to as the “axial” direction, while the “transverse” direction is in the x direction. Following conventional notation, the zero-degree fiber orientation of the composite runs in the x direction. This being the case, a unidirectional specimen with all fibers running the x direction will have all fibers running perpendicular to the load.

4.7.1 Results for the 76.2 mm (3.00 in) Long Specimens

4.7.1.1Normalized in-plane shear

Figure 4.8 shows the normalized in-plane shear stresses that occur in the three different laminates. As it is indicated by the contour lines, there exists a highly uniform state of shear stress between the notches in all three laminates. In all of the laminates, a somewhat oval shaped contour line between the notches shows that the normalized in-plane shear stress is between 0.9625 and 1.0375. There exist a small region of slightly higher stress (ranging from 1.0375 to 1.1125) at the notches for both the $[0/\pm45/90]_s$ and the $[\pm45]_{2s}$ laminates. This same stress exists in the results shown in previous research [5]. These results suggest that the state of in-plane shear stress is highly uniform for these laminates. The state of shear stress that has been predicted for these laminates is very similar to the predictions previously made for the existing shear test [5].

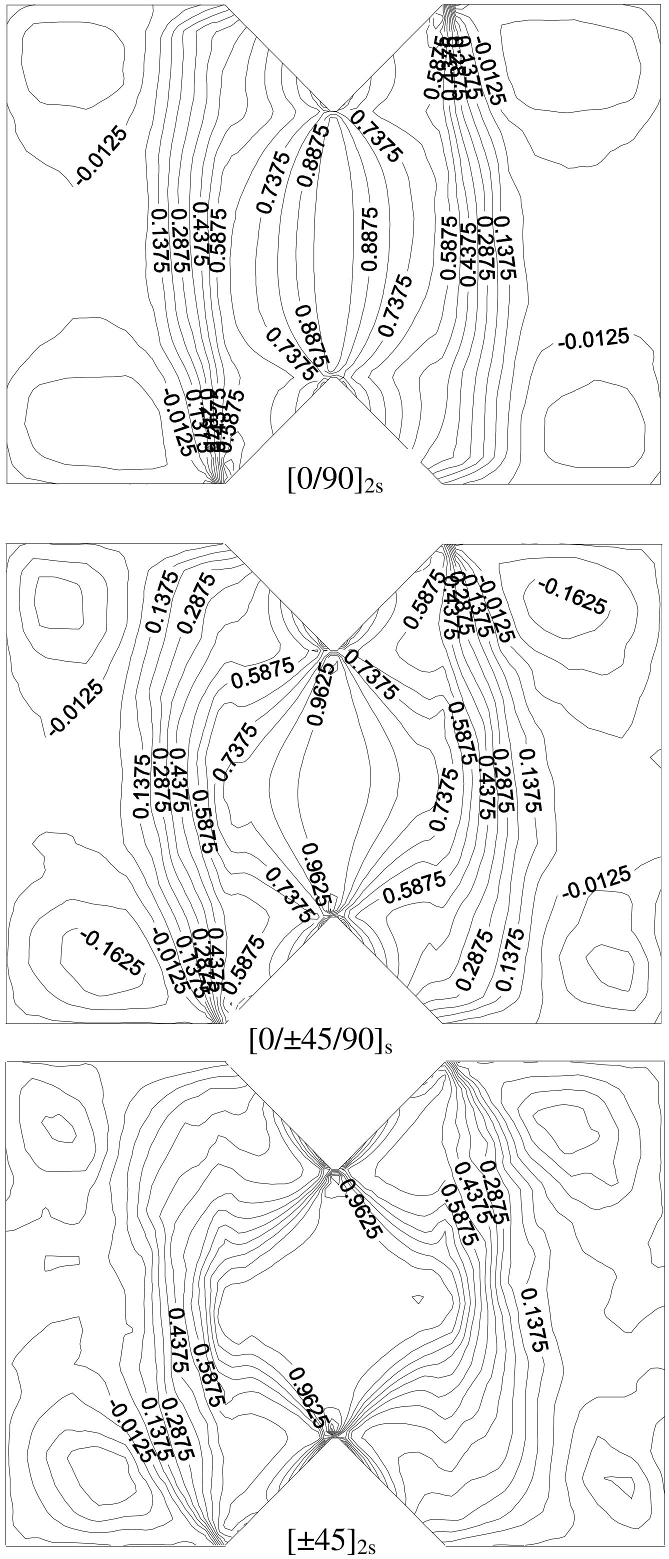


Figure 4.8 The normalized 76.2 mm (3.00 in) in-plane shear stress

4.7.1.2 Normalized transverse stress results

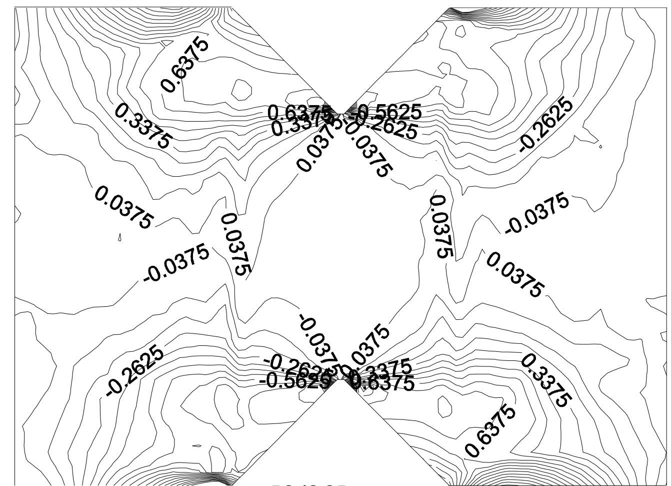
Figure 4.9 shows the plots of the normalized transverse normal stress results. For the $[0/90]_{2s}$ and $[0/\pm45/90]_s$ laminates, the normalized stresses are between -0.0375 and 0.0375 between the notches.

The $[\pm45]_{2s}$ laminate has low normalized transverse normal stresses between the notches, but there is a larger range of normalized stresses between the notches than the other two laminates. The normalized transverse normal stress ranges between -0.1125 and 0.1125 in-between the notches for the $[\pm45]_{2s}$ laminate.

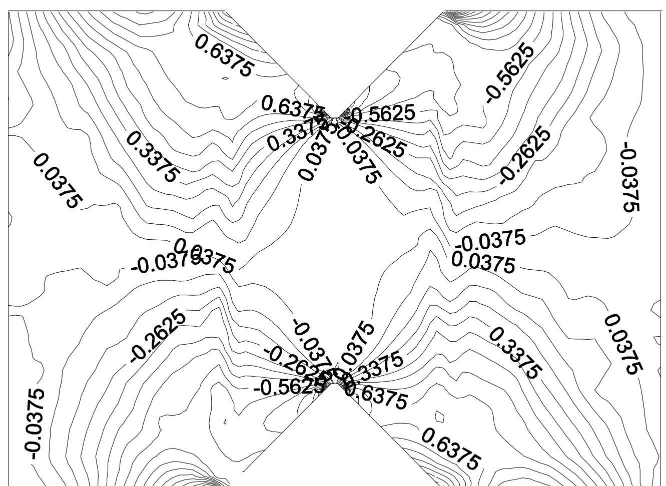
The slight change in the state of stress from the gage section to the gripping region of the specimens is believed to be due to the face-loaders. This is believed to be the case because all of the plots in the Laminate Effects Section are the nodal results on the faces of the laminate. When the gripping load is increased on the face loaders, the face loaders can induce some large stress concentrations at the edges of the gripping region. These stresses can be problematic if they cause premature failures at the grips. It is believed that these stresses also exist in the existing test method, but they are not shown in the finite element models done on the existing test method [5] because in the previous models the specimens are bonded directly onto the test fixture and the fixture/specimen interface is assumed perfect.

4.7.1.3 Normalized axial normal stress results

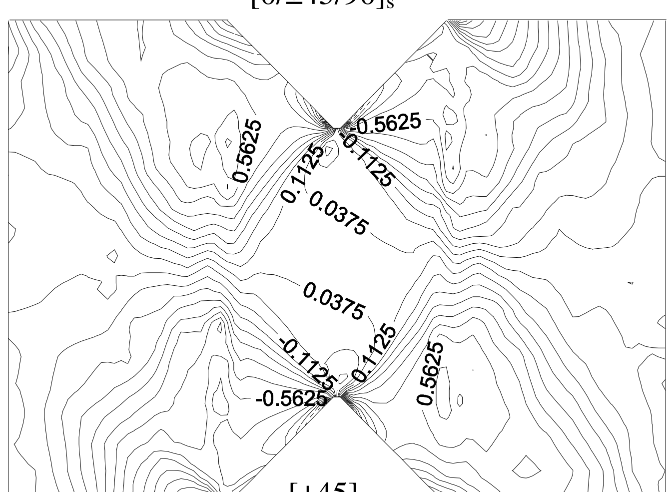
Figure 4.10 shows the normalized axial normal stress plots for the three laminates. The normalized axial normal stresses for the $[0/90]_{2s}$ laminate range from –0.0375 to 0.0375, similar to the normalized transverse normal stresses for the same laminate. The normalized axial normal stresses shown for the $[0/\pm45/90]_s$ laminate range between



$[0/90]_{2s}$



$[0/\pm45/90]_s$



$[\pm45]_{2s}$

Figure 4.9 The normalized 76.2 mm (3.00 in) transverse normal stress

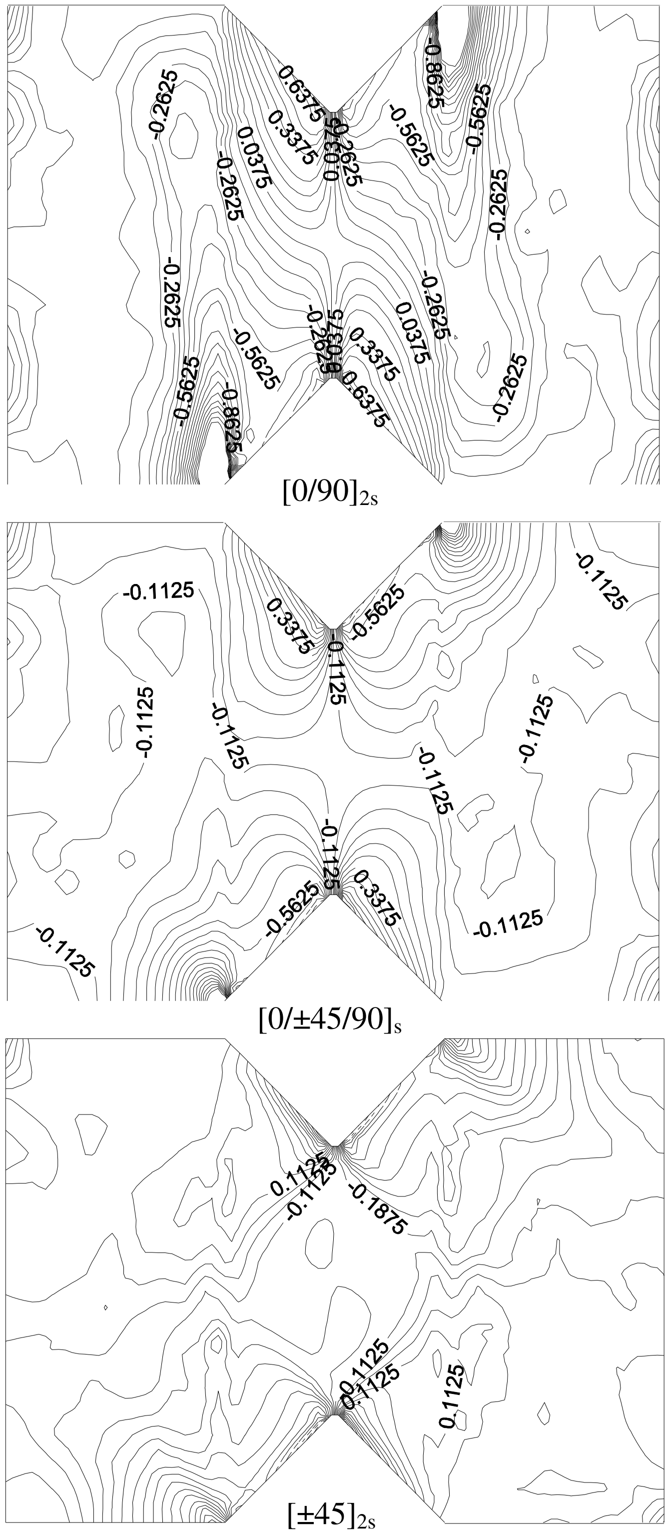


Figure 4.10 The normalized 76.2 mm (3.00 in) axial normal stress

-0.0375 and -0.1125. For the $[\pm 45]_{2s}$ laminate the axial normal stresses between the notches range between -0.2625 and -0.1125. These normalized axial normal stresses are higher those shown in previous work for the existing shear test. It is believed that these stresses are induced by the edge loaders.

4.7.1.4 Normalized axial normal stress results

Figure 4.10 shows the normalized axial normal stress plots for the three laminates. The normalized axial normal stresses for the $[0/90]_{2s}$ laminate range from –0.0375 to 0.0375, similar to the normalized transverse normal stresses for the same laminate. The normalized axial normal stresses shown for the $[0/\pm 45/90]_s$ laminate range between – 0.0375 and -0.1125. For the $[\pm 45]_{2s}$ laminate the axial normal stresses between the notches range between -0.2625 and -0.1125. These normalized axial normal stresses are higher those shown in previous work for the existing shear test. It is believed that these stresses are induced by the edge loaders.

One area of concern in all the plots for the normalized axial normal stresses is the large compressive stresses that occur at the right corner of the upper v-notch and the left corner of the bottom v-notch in each plot. These stresses are due to the edge loaders, which tend to load right on the corner of the specimen. It is known that when a load is applied on a point or a line, where the cross-sectional area is zero, the stress is theoretically infinite. It is also known that when this occurs in reality, one of the materials making contact will yield some and the force will be redistributed over newly formed area. While this slight yielding can be seen in some of the experimental results, these stresses can also lead to crushing at the corners.

4.7.2 Results for 127 mm (5.00 in) Long Specimens

4.7.2.1Normalized in-plane shear

Figure 4.11 shows the normalized in-plane shear stress for the three laminates, $[0/90]_{2s}$, $[0/\pm45/90]_{s}$, and $[\pm45]_{2s}$. The results here are similar to the results shown in the 76.2 mm (3.00 in) long results. The results for all three laminates show the normalized in-plane shear stresses range from 0.9625 to1.0375 in-between the notches.

4.7.2.2 Normalized transverse normal stress

Figure 4.12 shows the stress plots for the normalized transverse normal stresses for each for the three laminates. The [0/90]2s and [0/±45/90]s laminates show minimal transverse stresses between the notches with the normalized transverse normal stresses ranging from –0.0375 to 0.0375. The $[\pm45]_{2s}$ laminate shows a similar range of normalized transverse normal stresses between the notches as the 76.2 mm (3.00 in) model. The normalized transverse normal stresses between the notches in the $[\pm45]_{2s}$ laminate range between -0.0375 and 0.1125.

4.7.2.3 Normalized axial normal stress

Figure 4.13 shows the plots for the normalized axial normal stresses for the three laminates. The normalized axial normal stresses that are present between the notches for the $[0/90]_{2s}$ laminate range between –0.0375 and 0.0375, while the normalized axial normal stresses that are shown between the notches for the $[0/\pm45/90]_{s}$ laminate range between -0.1125 and -0.0375, and the normalized axial normal stresses between the notches for the [±45]2s laminate range between -0.2625 and -0.1125.

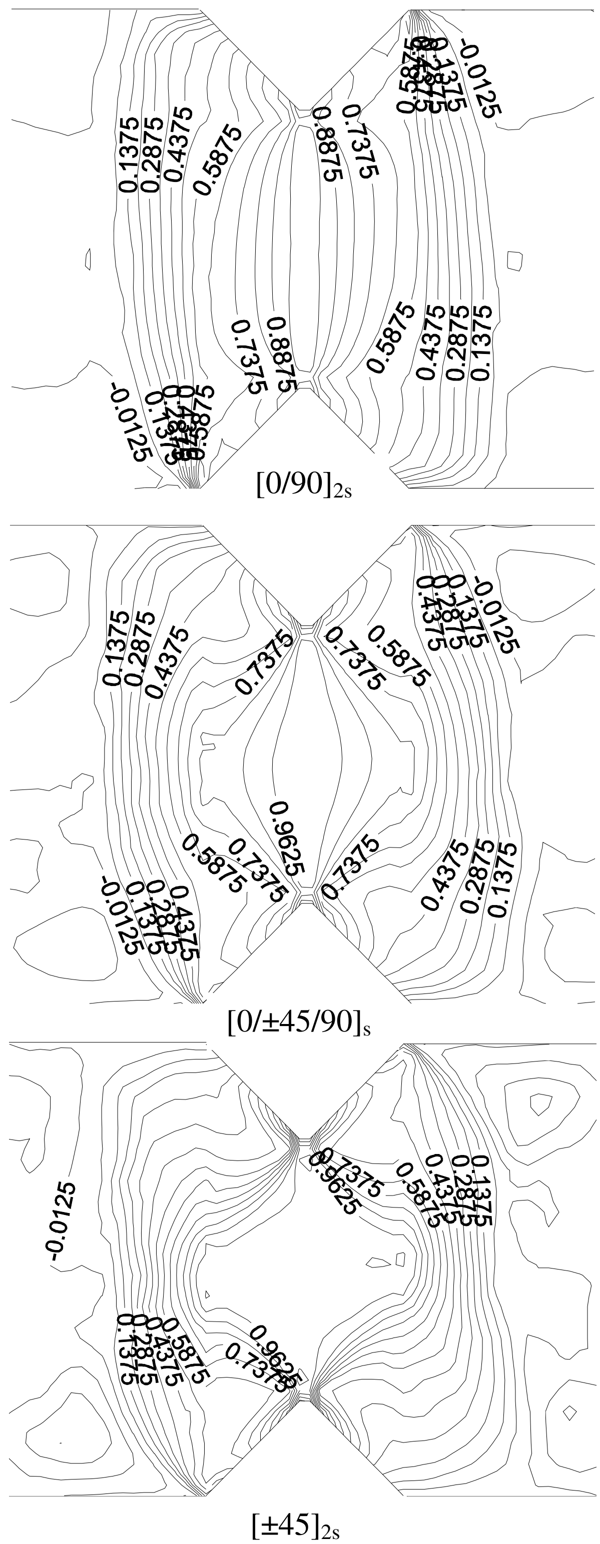
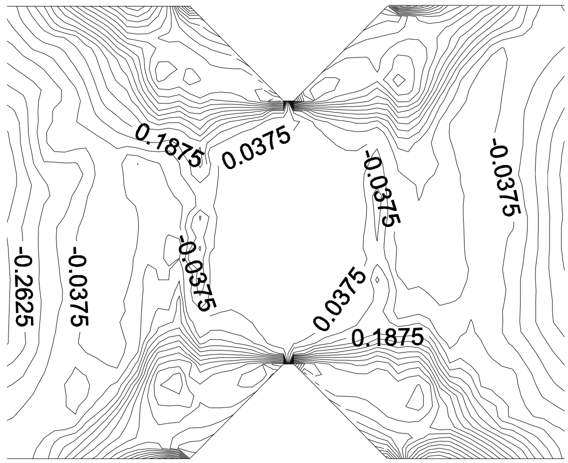
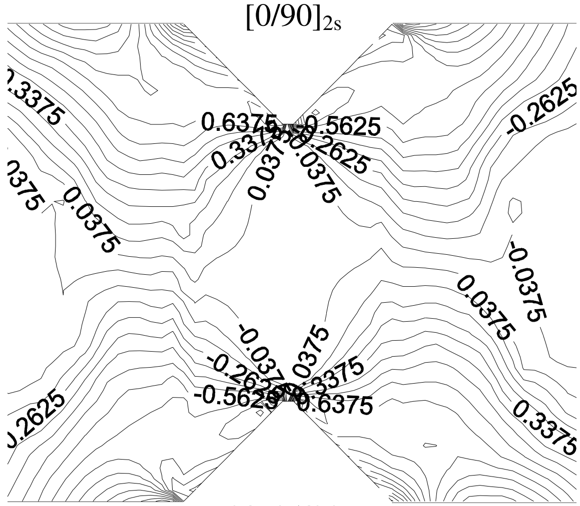


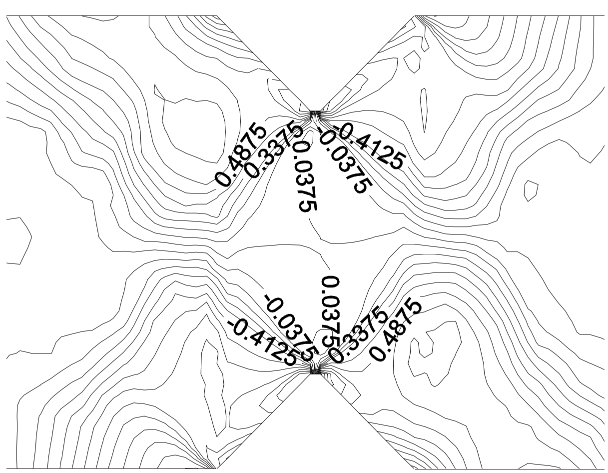
Figure 4.11 The normalized 127 mm (5.00 in) in-plane shear stress



[0/90]$_{2s}$



[0/±45/90]$_{s}$



[±45]$_{2s}$

Figure 4.12 The normalized 127 mm (5.00 in) transverse normal stress

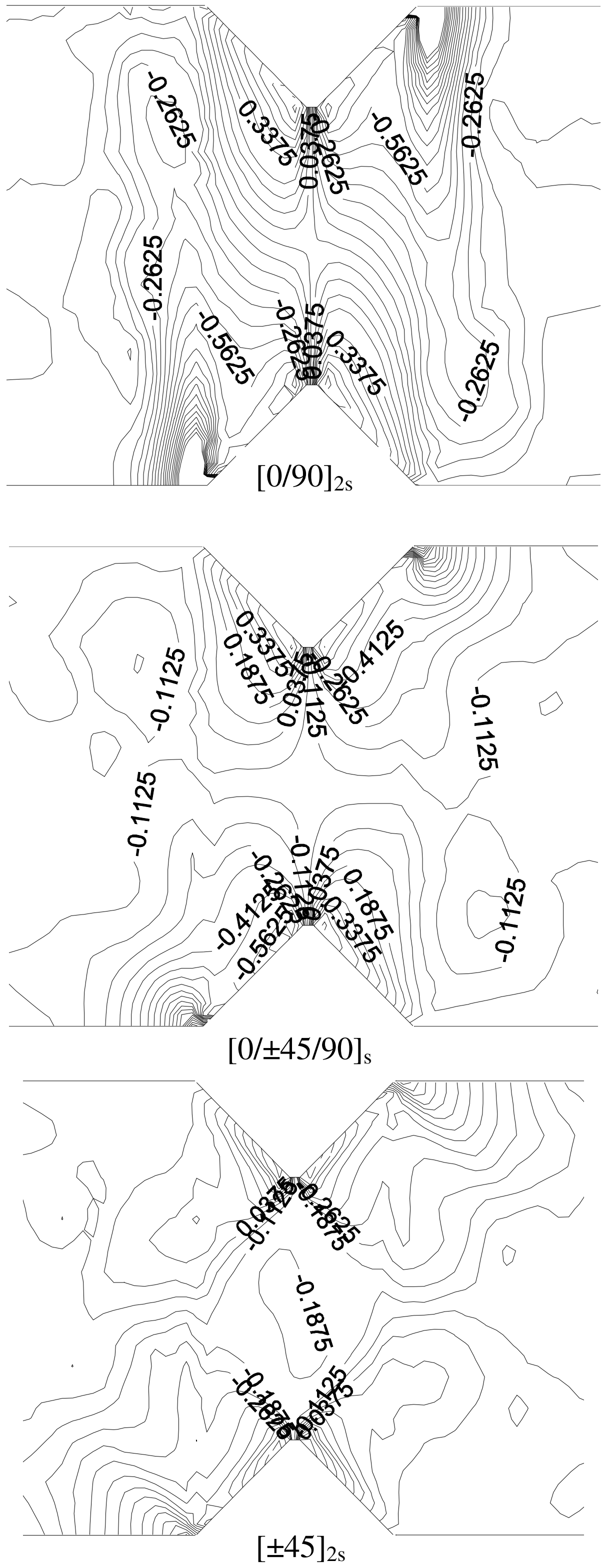


Figure 4.13 The normalized 127 mm (5.00 in) axial normal stress

Ideally, all of the normalized normal stresses in all of the above plots would range between -0.0375 and 0.0375. For the $[0/\pm45/90]_s$ and $[\pm45]_{2s}$ laminates for both 76.2 mm (3.00 in) and 127 mm (5.00 in) long specimens however, the normalized normal stresses are not always in this range. The normalized transverse normal stresses in the $[\pm45]_{2s}$ laminate for both the 76.2 mm (3.00 in) and the 127 mm (5.00 in) long models have areas of compression and tension in between the notches. The normalized axial normal stresses in between the notches in both the $[0/\pm45/90]_s$ and $[\pm45]_{2s}$ laminates are compressive for both the 76.2 mm (3.00 in) and the 127 mm (5.00 in) long models.

These normal stresses are not desirable, and they were not present in the finite element results shown in the previous work [5]. The normal stresses in the previous work were all between -0.0375 and 0.0375 in-between the notches for the V-Notched Rail Shear test method. In order to determine if these normal stresses can be reduced, the effects of the gripping load applied to the face loaders on the specimen were analyzed.

4.7.3 Undesirable Normal Stresses

The normalized normal stress plots that can be seen in Figure 4.9, Figure 4.10, Figure 4.12 and Figure 4.13 show that finite element model predicts non-zero states of normal stress between the notches for the $[0/\pm45/90]_s$ and the $[\pm45]_{2s}$ laminates. These normal stresses are undesirable. Ideally, the only stress that should exist between the notches would be the in-plane shear stress, and it should be uniform from notch to notch. In order to determine the cause of these undesirable stresses, the 127 mm (5.00 in) long Combined Loading model was performed for the $[0/\pm45/90]_s$ and the $[\pm45]_{2s}$ laminates with some changes in the contact modeling. First, the laminates were modeled with only face loading, (similar to the V-Notched test) and then only with edge loading (similar to the Iosipescu test).

Figure 4.14 shows the plots for the in-plane stresses for the $[\pm 45]_{2s}$ laminate when modeled in 127 mm (5.00 in) long specimens that are tested with either face loading only or edge loading only. Figure 4.15 shows the three the plots for the in-plane stresses for the $[0/\pm 45/90]_s$ laminate when modeled in 127 mm (5.00 in) long specimens that are tested with either face loading only or edge loading only. The face loading only plots are shown on the left, while the edge loading plots are shown on the right of each figure.

In Figure 4.14, it is apparent that the face-loading only model produces a much more desirable state of stress than the edge loading only model. In the normalized in-plane shear stress plots, the face loading only model has a highly uniform state of in-plane shear stress, while the edge loading only model has a much less uniform state of in-plane shear stress.

The plots for both the normalized transverse and axial normal stresses also show the face loading only model having a highly uniform state of low normalized stresses. The normalized transverse and axial normal stresses range between -0.0375 and 0.0375 between the notches for the face loading only model. The edge loading only model, however, has nonuniform states of normalized transverse and axial normal stresses. The normalized transverse normal stress plot for the edge loading model shows both tensile and compressive stresses between the notches. The normalized axial normal stress plot for the edge loading only model shows non-uniform, and relatively high compressive stresses between the notches.

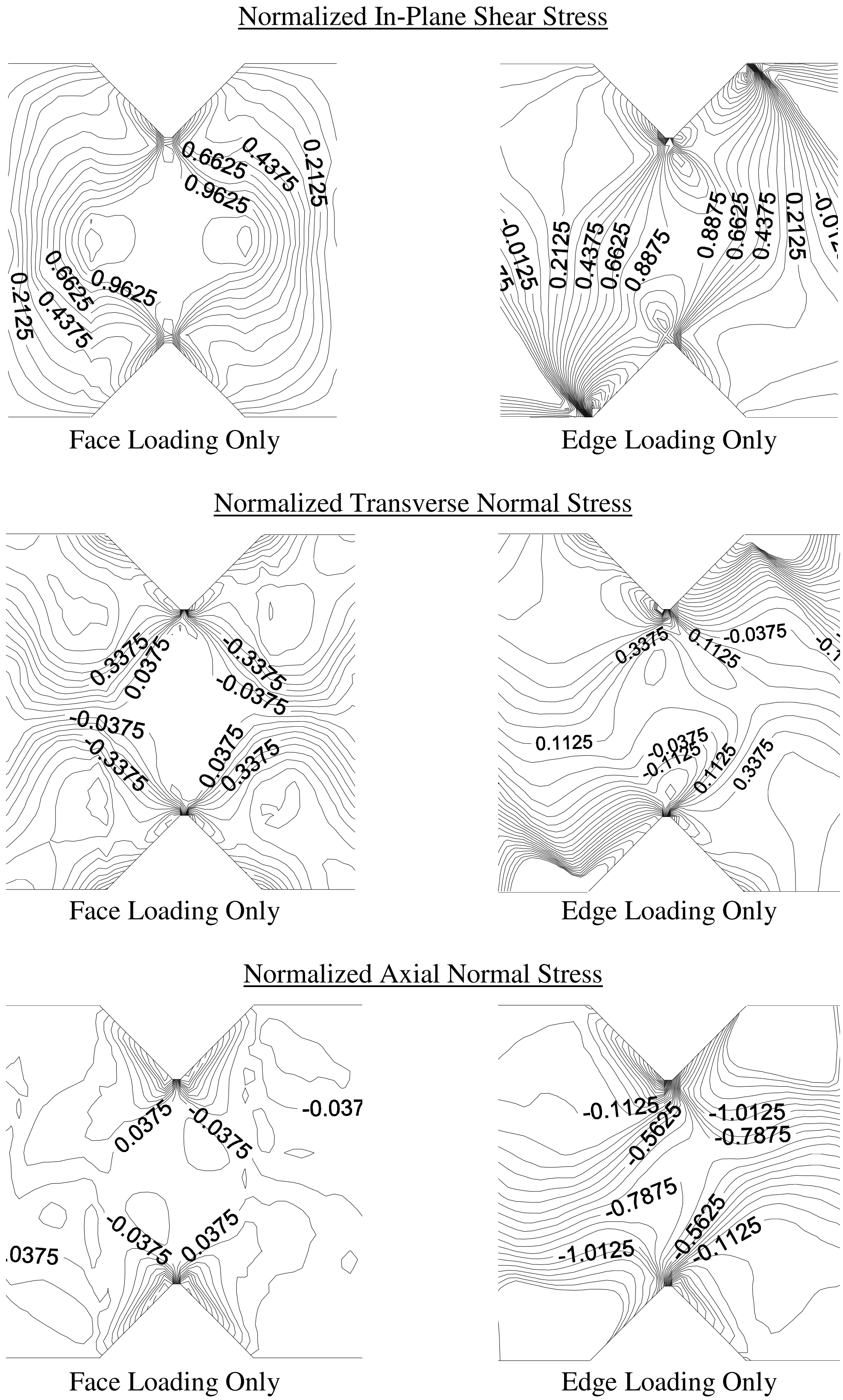


Figure 4.14 The [±45]$_{2s}$ laminate modeled in 127 mm (5.00 in) long specimens with load applied by face loading only (left) and edge loading only (right)

Figure 4.15 compares the differences in the in-plane stresses for the $[0/\pm45/90]_s$ laminate when tested in 127 mm (5.00 in) long specimens using either face or edge loading only. It is apparent in this figure that, similar to the $[\pm45]_{2s}$ laminate, the face loading only model predicts a much more desirable state of stress in the specimen than the edge loading only model. The results for the $[0/\pm45/90]_s$ laminate are similar to the results for the $[\pm45]_{2s}$ laminate, but the degree to which the in-plane stresses are adversely affected by edge loading only is slightly less for the $[0/\pm45/90]_s$ laminate.

From these results it can be seen that the edge loaders are the cause of the undesirable normal stresses that exist in the combined loading plots discussed earlier. These results agree with research done by Burst and Adams on the viability of an Iosipescu modification for thin-film adhesive shear testing [10]. The quasi-isotropic results shown here in Figure 4.15 can be compared to the bulk material results in Burst and Adams' research shown in Figures 10, 12 and 13 of their research [10]. In Burst and Adams' research, the normalized in-plane shear stress between the notches ranges between 0.96875 and 1.0625. Here, in Figure 4.15 the normalized in-plane shear stress that is predicted between the notches ranges between 0.9625 and 1.1125. In Burst and Adams' research, the normalized transverse normal stress that is predicted between the notches ranges between -0.10 and 0.20. Here, in Figure 4.15 the normalized transverse normal stress that is predicted between the notches ranges between -0.2625 and 0.2625. In Burst and Adams' research, the normalized axial normal stress that is predicted between the notches ranges between -0.25 and -0.20. Here, in Figure 4.15 the normalized axial normal stress that is predicted between the notches ranges between -0.4875 and 0.4125.

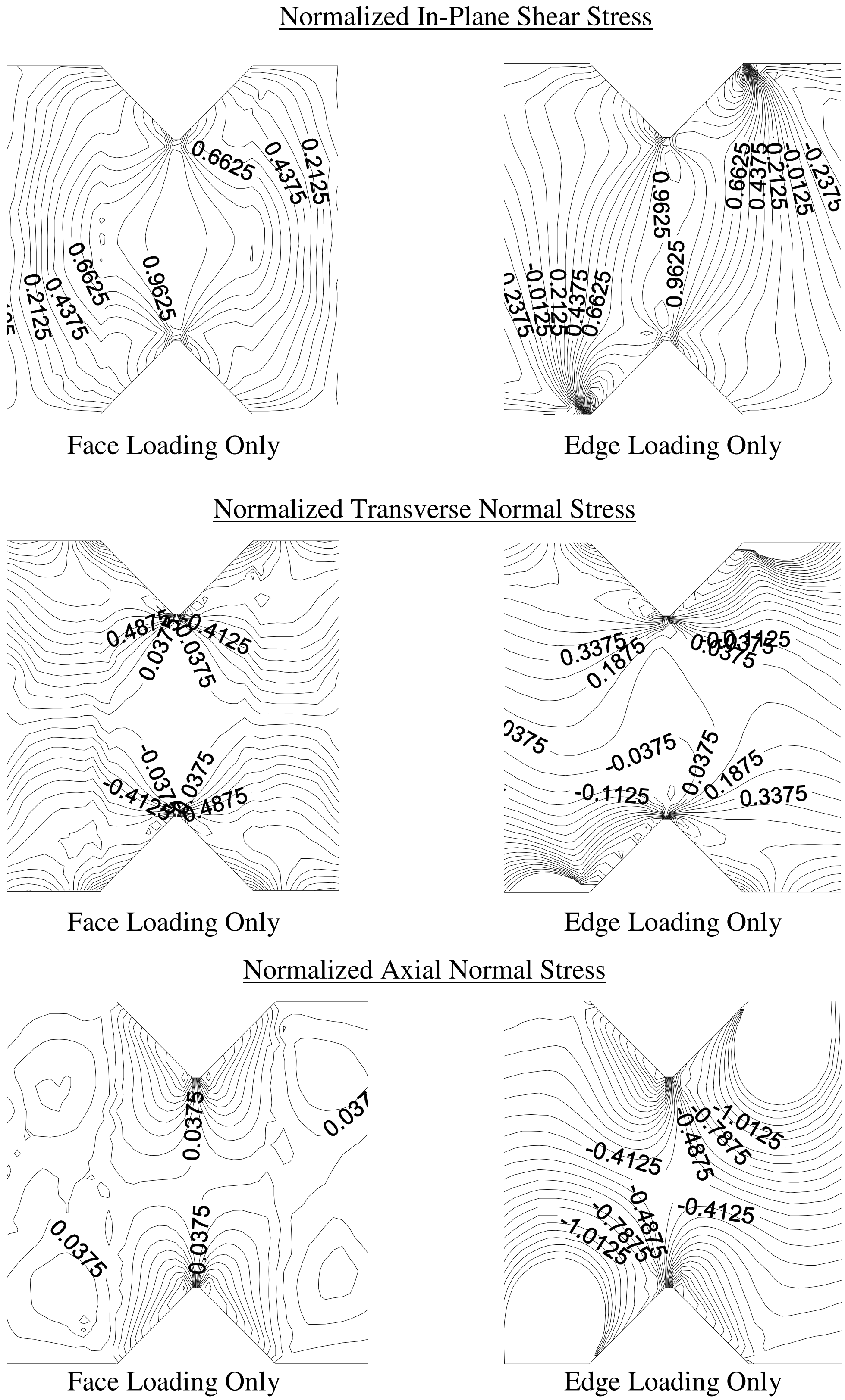


Figure 4.15 The $[0/\pm45/90]_s$ laminate modeled in 127 mm (5.00 in) long specimens with load applied by face loading only (left) and edge loading only (right)

The largest difference in these results from those of Burst and Adams is the normalized axial normal stresses. The cause for this could be partially due to the difference in material properties, but it is mostly due to the difference in the length of the specimens. The specimen length-to-notch length ratio for the specimens modeled in this research is much smaller than it is for the Iosipescu specimens modeled in Burst and Adams' research. A smaller specimen length-to-notch length ratio will result in much higher compressive loads being applied by the edge loaders near the notches. The reason for this will be explained in greater detail in Section 6.3.2.4.

4.8 Laminate Thickness Effects

The overall purpose of this thesis was to determine what improvements can be made on the existing V-Notched Rail Shear test method so that it can test stronger laminates. Many laminates are made stronger simply by adding plies and increasing the thickness. With the increase in the thickness of laminates, the state of stress through the thickness became a concern because the existing shear test applies the load only through the faces of the specimens. For this reason, the state of stress through the thickness of the laminates was analyzed for all three laminates that have been modeled up to this point (cross-ply, quasi-isotropic, and ±45) using the existing shear test and the Combined Loading test. 76.2 mm (3.00 in) long and 127 mm (5.00 in) long specimens were modeled in the Combined Loading test.

These models were made using the fixtures illustrated and described in Section 3.4 in the previous chapter. The specimens were modeled in these fixtures as two halves of a specimen. The specimen halves were made by cutting the specimen from notch to notch. Figure 4.16 shows a specimen half loaded into half of the ASTM D 7078 model.

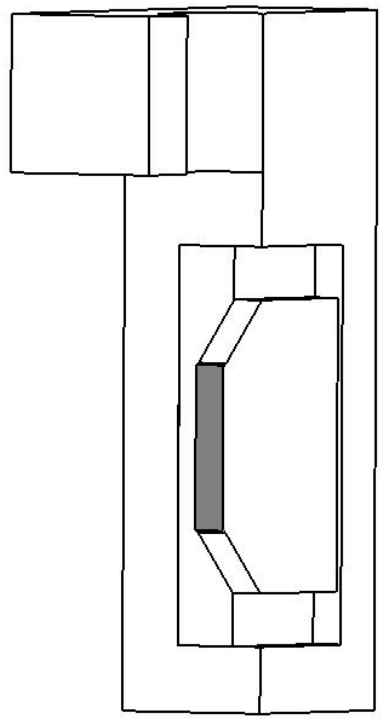


Figure 4.16 Half of the specimen loaded into one half of the fixture

The two specimen halves were attached to each other in the finite element model using bonded contact elements. The reason for creating the model this way was so that there would be a flat surface from which the nodal stress results could be taken. This flat surface is shaded in grey in Figure 4.16 and it is where the nodal results were taken from to make the plots shown in the following figures.

Figures 4.17 through 4.19 show the contour plots of the normalized in-plane shear stress for the three different laminates, cross-ply, quasi-isotropic, and ±45, being modeled using the ASTM D 7078 model, the Combined Loading model with 76.2 mm (3.00 in) long specimens, and the Combined Loading model with 127 mm (5.00 in) long specimens. The surfaces shown in the plot are the cross-sectional areas of the specimens between the notches. This is the smallest cross-section on the specimens and is the location where the specimen is designed to fail.

The thickest specimen that can fit into the ASTM D 7078 fixture would be 12.7 mm (0.50 in) thick. Since this is the case, all of the specimens modeled to analyze the thickness effects are 6.35 mm (0.25 in) thick and take advantage of symmetry. In each of the plots shown, the right side of the plot is the outer face of the specimen and the left side is the center. The separate laminas are not modeled here, but the specimens modeled are assumed to be a homogeneous material with orthotropic properties that correspond to those found in the specific laminate being modeled. The material properties for these laminates can be found in Table 3.1.

Figure 4.17 shows the results for the cross-ply laminate being modeled using the three different test methods. For this laminate, the state of shear is quite uniform for all the test methods. The majority of each cross section has a normalized in-plane shear stress between 0.9625 and 1.0375. From these results it is believed that the state of in-plane shear stress through the thickness is equally uniform for any of the three test methods when testing cross-ply laminates.

Figure 4.18 shows the results for the quasi-isotropic laminate being modeled using the three different test methods. All of the test methods show a greater change through the thickness in normalized in-plane shear stress than was seen in the cross-ply laminate. The ASTM D 7078 model shows the greatest drop in shear stress through the thickness with almost all of the normalized shear stress dropping below 0.9625 at the center of the specimen (the left side of the plot). The two Combined Loading models show a somewhat better state of normalized in-plane shear stress at the center with the

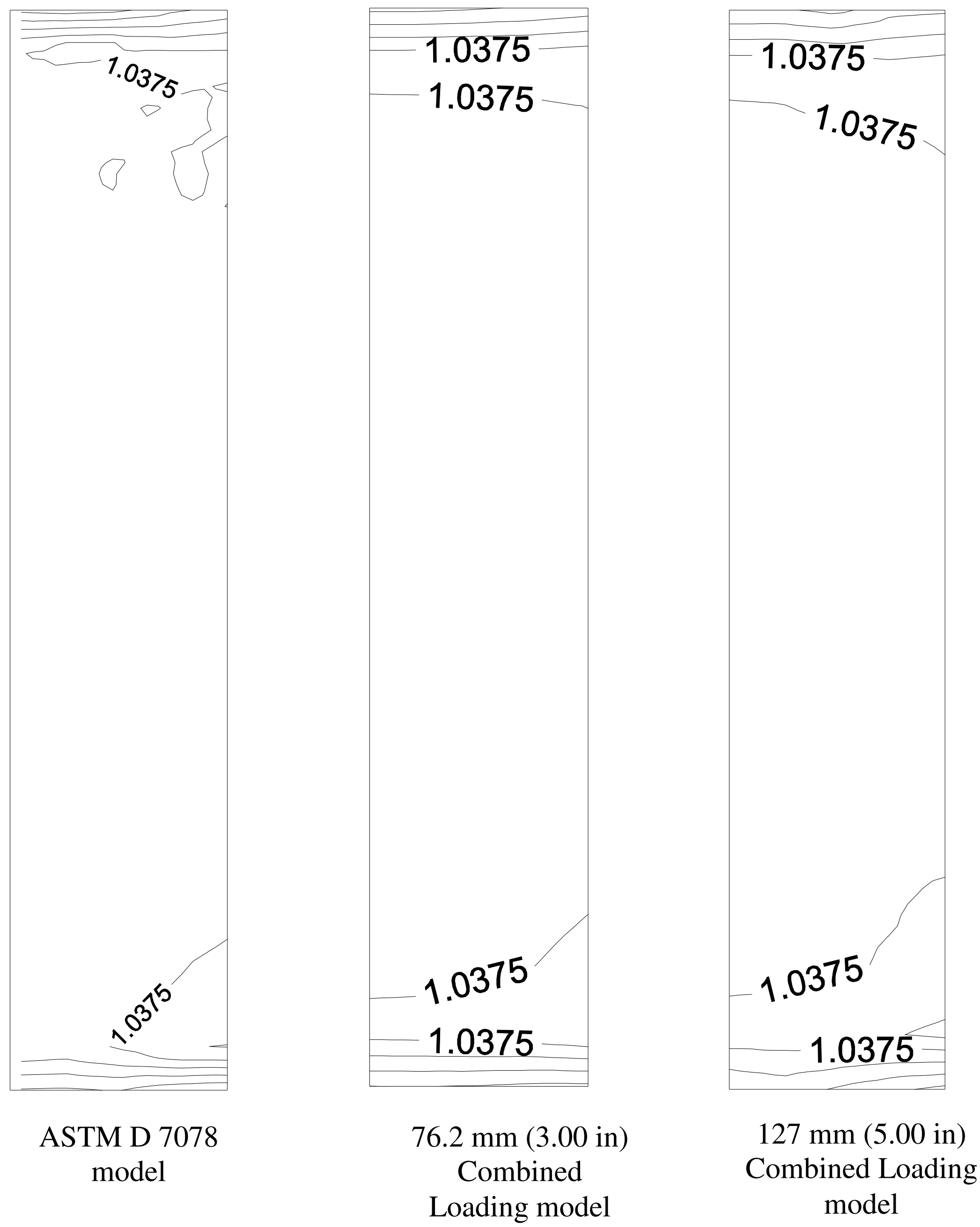


Figure 4.17 The normalized in-plane shear stress for the cross-ply laminate

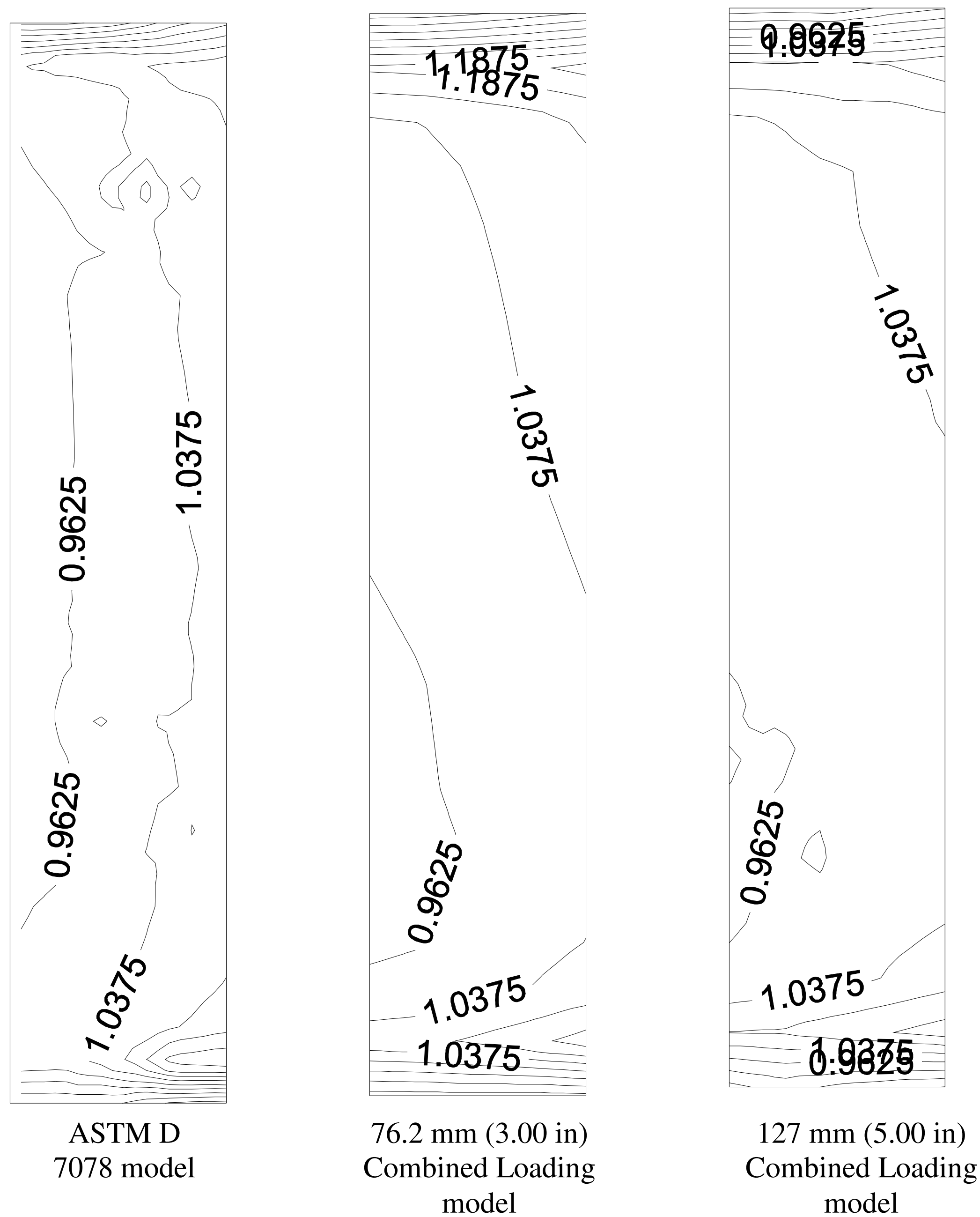


Figure 4.18 The normalized in-plane shear stress for the quasi-isotropic laminate

normalized shear stress dropping below 0.9625 in about a third of the height in the 76.2 mm (3.00 in) long specimen in the Combined Loading model and less than a quarter of the height in the 127 mm (5.00 in) long specimen in the Combined Loading model. From this the conclusion is drawn that the of these three test methods, the Combined Loading test method using 127 mm (5.00 in) long specimens will produce the most uniform state of in-plane shear stress through the thickness for the quasi-isotropic laminate.

Figure 4.19 shows the results for the ±45 laminate being modeled using the three different test methods. It can be seen in this figure that the stress gradients are slightly higher for this laminate than the previous two, regardless of the test method. The ASTM D 7078 model has the greatest changes in stress with the normalized shear stress starting between 1.0375 and 1.1125 across most of the face, then decreasing to value between 0.8875 and 0.9625 across most of the center (the left side). The normalized shear stress in the 76.2 mm (3.00 in) long specimen in the Combined Loading model starts on about half of the face of the specimen between 1.0375 and 1.1125 then decreases to a value between 0.8875 and 0.9625 across about half of the height of the cross-section at the center of the specimen. The normalized shear stress for the 127 mm (5.00 in) long specimen in the Combined Loading model is very similar to the stress shown in the 76.2 (3.00 in) long specimen in the Combined Loading model. Any differences are minor.

From these results, it can be seen that for the ±45 laminate the finite element method predicts that the ASTM D 7078 model will have a slightly less uniform state of shear stress than the two Combined Loading models. This leads to the conclusion that of these three test methods, the 76.2 mm (3.00 in) long specimen and the 127 mm (5.00 in)

ASTM D
7078 model

76.2 mm (3.00 in)
Combined Loading
model

127 mm (5.00 in)
Combined Loading
model

Figure 4.19 The normalized in-plane shear stress for the ±45 laminate long specimen both tested in the Combined Loading test fixture will produce equally uniform states of in-plane shear stress through the thickness for the ±45 laminate.

5. SPECIMEN FABRICATION AND TESTING METHODOLOGIES

5.1 Introduction

For this study, one commercially available thermoset composite material was used to fabricate the laminates that were tested. Several different geometries were used for the specimens. Laminate production and subsequent cutting out of the specimens is explained in this chapter. Initial testing was done using the V-Notched Rail Shear test fixture, ASTM D 7078 [2]. After review of initial testing and finite element results, a new test fixture was designed and built. An explanation of the new test fixture along with detailed machine drawings of all its parts are given in this chapter.

5.2 Material Systems Tested

The material used for making specimens in this study was a carbon fiber pre-preg manufactured by HEXCEL Advanced Composites known as IM7/8552. It is a high performance, intermediate modulus pre-preg tape. The cured thickness of one lamina is roughly 0.305 mm (0.012 in.). The material was used in 12 different lay-ups for testing. They are: $[0/90]_{s}$, $[0/90]_{2s}$, $[0/90]_{3s}$, $[0/90]_{4s}$, $[0/\pm45/90]_{s}$, $[0/\pm45/90]_{2s}$, $[0/\pm45/90]_{3s}$, $[0/\pm45/90]_{4s}$, $[\pm45]_{2s}$, $[\pm45]_{3s}$, $[\pm45]_{3s}$, $[\pm45]_{4s}$, and $[\pm45]_{5s}$, These lay-ups can be categorized into three different types of laminates with 4 different thicknesses per group. The different types of laminates are $[0/90]_{ns}$ (cross-ply), $[0/\pm45/90]_{ns}$ (quasi-isotropic), and $[\pm45]_{ns}$ (±45). Where n is the number of times the lay-up inside the square brackets is repeated, and s indicates the lay-up is symmetric. In the case of the $[0/90]_{ns}$ and

$[0/\pm45/90]_{ns}$ groups (the cross-ply and the quasi-isotropic lay-ups, respectively), n =1, 2, 3, and 4. In the case of the $[\pm45]_{ns}$ group, n = 2, 3, 4, and 5.

5.3 Panel Fabrication

The laminates were made by first cutting the material into squares measuring 305 mm (12 in) by 305 mm (12 in). They were then placed into well-and-plunger mold. The mold is made up of top and bottom pieces as well as four side pieces. All parts of the tool are made out of mild steel. The bottom piece measures 305 mm (12 in) by 305 mm (12 in) by 12.7 mm (0.5 in) and has five, evenly spaced, tapped holes on each of the four sides into which ¼ in - 20 bolts were placed to secure the side pieces to the bottom piece. The top piece measures 305 mm (12 in) by 305 mm (12 in) by 19 mm (0.75 in). The side pieces measure 38.1 mm (1.50 in) by 12.7 mm (0.50 in) and are 305 mm (12 in) long for the short pieces and are 330 mm (13 in) long for the long pieces. Each of the side pieces have five, evenly spaced 6.35 mm (0.25 in) holes drilled in them to attach them to the bottom piece. Each part of the tool is coated with an adhesive-backed Teflon tape to allow the part to be removed from the tool. After coating each piece with the Teflon tape, the side pieces are attached to the bottom piece.

The laminas are placed in the correct order for the specific lay-up into the cavity made by the four side pieces bolted onto the bottom piece. The top piece is then placed on top of the laminas, and acts as a plunger going into the space left by the cavity. Once the laminas are inside the tool, the tool is placed into a Carver heated hydraulic press. The press's heated platens measure 305 mm (12 in) by 305 mm (12 in). The mold is placed into the press and the hydraulic jack is set to a low pressure so that the top and the bottom platens are just contacting the mold, and the temperature of both the top and the bottom platens is set to 121° C (250 °F). After one hour the pressure on the platens is increased to 689.5 kPa (100 psi) and the temperature of each platen is increased to 176.7°C (350 °F). After three more hours the platens are turned off and left to cool with the tool still in the press with the 689.5 kPa (100 psi) pressure still applied. Once the press has cooled to room temperature, the tool is removed from the press and the newly made laminate is removed from the tool.

5.4 Specimen Fabrication

After the laminates were fabricated, they were cut into specimens using an Omax water jet cutter. The water jet cutter can make two-dimensional cuts onto a flat sheet of material using a high-velocity stream of water that is carrying a grit material. The cutting instructions for the water jet come from a two-dimensional computer file made in SolidWorks. This file is then imported into the Omax software and it is used to guide the nozzle on the water jet to make the appropriate cuts for the specimen. Due to the nature of the cuts made by the water jet, the laminates will delaminate when the water jet pierces the laminate to initiate a cut. The delaminations are generally round and have a diameter of roughly 12.7 mm (0.50 in). For this reason, it is necessary to reduce the number of times the water jet pierces the laminate. This is done by connecting the specimens in the computer file with thin tabs. An example file with the thin tabs can be seen in Figure 5.1. The result is the water jet will only need to make one pierce and multiple specimens will be cut out with one cut, resulting in a long string of specimens connected to each other with thin tabs. Note the tabs in Figure 5.1 that connect each row of specimens. This

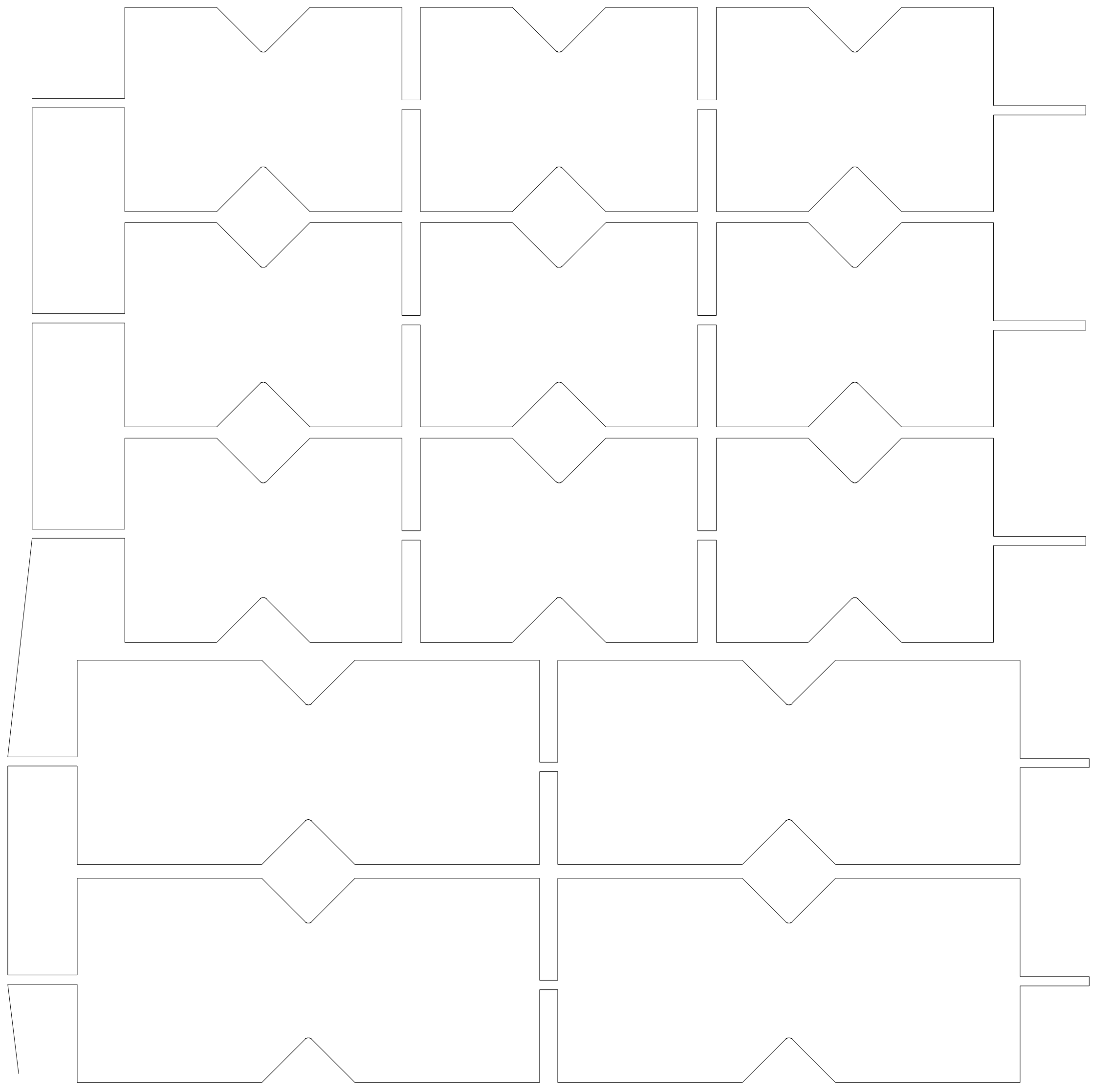


Figure 5.1 An example of the cutting instructions for the water jet

figure shows both 76.2 mm (3.00 in) long and 127 mm (5.00 in) long specimens. The vertical lines that connect the tabs on the far left of the figure and the vertical lines that connect the top and bottom of each tab on the far right are actually not cutting instructions for the water jet, but simply displacement instructions to tell the machine where to start the next cut. What this means is that when the water jet is done cutting, all of the specimens are still connected to the leftover material.

Once the water jet is done cutting out the specimens, they are separated from the excess material and from each other. This is done using a Husky water-cooled tile saw with a diamond-coated blade. The water cooling capabilities of the tile saw are also useful for catching the carbon fiber dust that is created from the cutting. The quality of the cuts that separate the specimens from each other is inconsequential because the edges being cut (the left and right side of each specimen) are of no great importance other than they should be relatively parallel to each other and relatively perpendicular to the top and bottom edges.

Due to the nature of the cutting process done on the water jet, the edges of the specimen can be tapered through the thickness. This can be problematic for the top and the bottom edges of the specimens because they are used apply load into the specimen using the edge loaders on the Combined Loading fixture. To ensure that the top and bottom edges of the specimens are perpendicular to the faces, and that they are all parallel, the specimens were placed in the vice of a mill and a grinding drum was passed along the top and bottom edges. This greatly reduces the taper to an acceptable level.

The final step in preparing the specimens for testing is the sanding of the faces. The mold used to make the laminates has dimples in it. These dimples cause corresponding protrusions to form on the faces of the laminates. Having these protrusions can prevent the face loading grips from properly gripping the specimens. For this reason, the faces of the specimens were sanded to allow the face loaders to evenly grip all of the specimens' face-loading surfaces. In Figure 5.2 and Figure 5.3 the same specimen can be seen before and after sanding, respectively. Note the protrusions that can be seen in Figure 5.2, and how they are sanded off in Figure 5.3.

While it was stated that sanding was the final step in preparing the specimens, in truth it was not always necessary. About half-way through production of the specimens, it was discovered that adding an extra layer of a permeable Teflon cloth between the outer laminas and the mold creates a buffer between the laminate and the mold, and the protrusions do not form on the faces of the laminates. For this reason, the specimens made in the latter half of this study did not require sanding.

5.4.1 Specimen Geometries Tested

Initial tests were performed on the rectangular specimens. These tests were done to determine the coefficient of friction between the fixture's face-loaders and the specimens' gripping surfaces. Tests were also done on v-notched specimens measuring 76.2 mm (3.00 in) long and 127 mm (5.00 in) long.

5.4.1.1 Rectangular friction specimens

The rectangular friction specimens are similar to the v-notched specimens in dimensions, but they are missing the notches. These specimens were fabricated to ensure that when they were tested in the current V-Notched test fixture they would slip rather

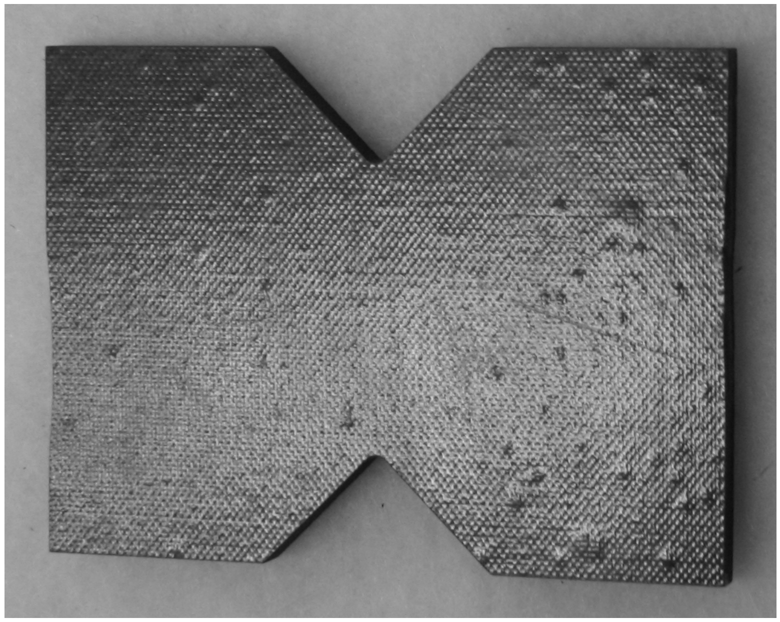


Figure 5.2 A 76.2 mm (3.00 in) long specimen shown prior to sanding. Note the protrusions on the surface.

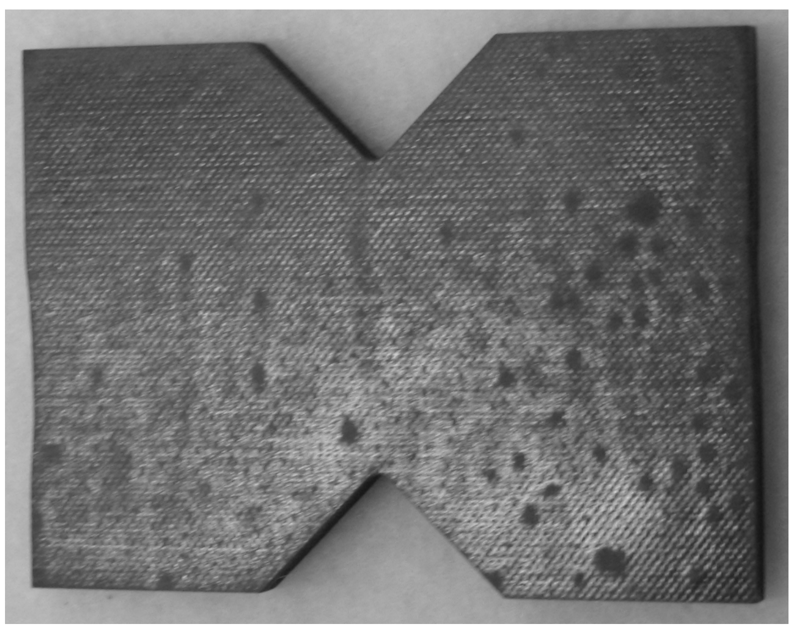


Figure 5.3 A 76.2 mm (3.00 in) long specimen shown after being sanded

than break. The loads at which these specimens slipped were then used to determine the coefficient of friction between the face loaders and the specimens. This is discussed in further detail in Chapter 4 and Chapter 6 of this thesis. The dimensions of the Rectangular Friction Specimen are 76.2 mm (3.00 in) long by 55.88 mm (2.20 in) high with 25.4 mm (1.00 in) on each side being placed in the grips of the fixture. A drawing of the rectangular friction specimen can be seen in Figure 3.2.

5.4.1.2 76.2 mm (3.00 in) V-notched specimen

The 76.2 mm (3.00 in) long V-notched specimens have dimensions that are specified in ASTM D 7078. The specimen is 76.2 mm (3.00 in) long, 55.88 mm (2.20 in) high, and has a 12.7 mm (0.50 in) deep v-shaped notch cut out of the top and the bottom of the of the test region. A drawing can be seen of the 76.2 mm (3.00 in) long specimen in Figure 3.4.

5.4.1.3 127 mm (5.00 in) V-notched specimen

The 127 mm (5.00 in) V-notched Specimen is essentially the same as the 76.2 mm (3.00 in) V-notched Specimen, but with 25.4 mm (1 in) added to each of the gripping regions. The increased gripping regions are used to help mitigate any slipping that might occur when the specimen is subjected to high loads. The 127 mm (5.00 in) long V-notched specimen measures 127 mm (5.00 in) long, 55.88mm (2.20 in) high, and has the same v-notches at the center of the specimen that the 76.2 mm (3.00 in) long specimen has. A drawing of the five-inch specimen can be seen in Figure 3.5.

5.5 Test Fixtures

Two test fixtures were used in this study. The first was the current V-Notched Rail Shear Fixture used in ASTM D 7078 [2], and is manufactured by Wyoming Test Fixtures, Inc. The second is a Combined Loading modification of the current fixture known as the Combined Loading fixture. The modifications include the addition of edge loaders and longer face loaders.

5.5.1 The V-Notched Rail Shear Test Fixture

The V-Notched Rail Shear Test Fixture was developed at the University of Utah as an answer to the request by the materials testing community that there be a shear test that can validly test specimens at higher loads and also test coarser textile weaves than the Iosipescu test method, ASTM D 5379 [1]. The fixture has two identical halves that each measure 133 mm (5.25 in.) high, 63.5 mm (2.50 in) wide, and 76.2 mm (3.00 in.) deep. Each half is L-shaped and has a cavity cut out of it for the frictional face-loading plates sit. The frictional face loading plates have a thermal-sprayed surface treatment which creates a roughened gripping surface with a roughness similar to 60 grit sand paper. There are three bolts on each side of each half of the fixture that apply the normal force necessary to get the frictional force that holds the specimen in the fixture. The fixture can be seen in Figure 1.2 along with a test specimen.

5.5.2 The Combined Loading Test Fixture

The new Combined Loading test fixture that was designed and built is similar to the current V-Notched Rail Shear test fixture. It has the same general L-shape and has ½ in -20 allen head bolts for applying the clamping forces to the specimens. The face loaders in this fixture received the same thermal-sprayed surface treatment for the gripping surfaces that was used on the face loaders of the V-Notched Rail Shear fixture. The major differences in this new fixture are the depth of the cavity for the face loading plates and the addition of edge loaders similar to those used in the Iosipescu shear fixture, ASTM D 5379 [1]. Figure 5.4 shows the completed fixture with two possible specimens. As it can be seen in this figure, this fixture is made up of many more parts than the V-Notch fixture that were then assembled. This was done in order to simplify the manufacturing of this fixture. Figure 5.5 shows an exploded view a one of the halves of the Combined Loading fixture. In Figure 5.5 the different components of this fixture are labeled with the number of the figure that contains that component's machine drawings. This figure is shown in order to explain how the components of the fixture fit together. Each part was made out of mild steel except for the side pieces which were made out of 4140 steel. All of the parts were machined on the Omax water jet and using a mill.

Figure 5.6 is a drawing of the side pieces, of which four are required. Each of the side pieces has four ½ in -20, tapped holes for the bolts that apply the clamping force on the face loaders. Figure 5.7 is a drawing of the top pieces, of which two are required. The top pieces have 1"-12 tapped hole for connecting the rest of the fixture to the load frame.

Figure 5.8 shows drawings of the middle, angled pieces and the top edge-loading pieces. These parts work together to create the edge loading. The idea to create the edge loading in this manner was taken from the Iosipescu fixture [1]. The middle, angled piece has a 10 degree slope on the bottom, as does the top of the top edge-loading piece. When the top edge-loading piece is driven by a 5/16 in - 24 bolt that also sits on a 10 degree

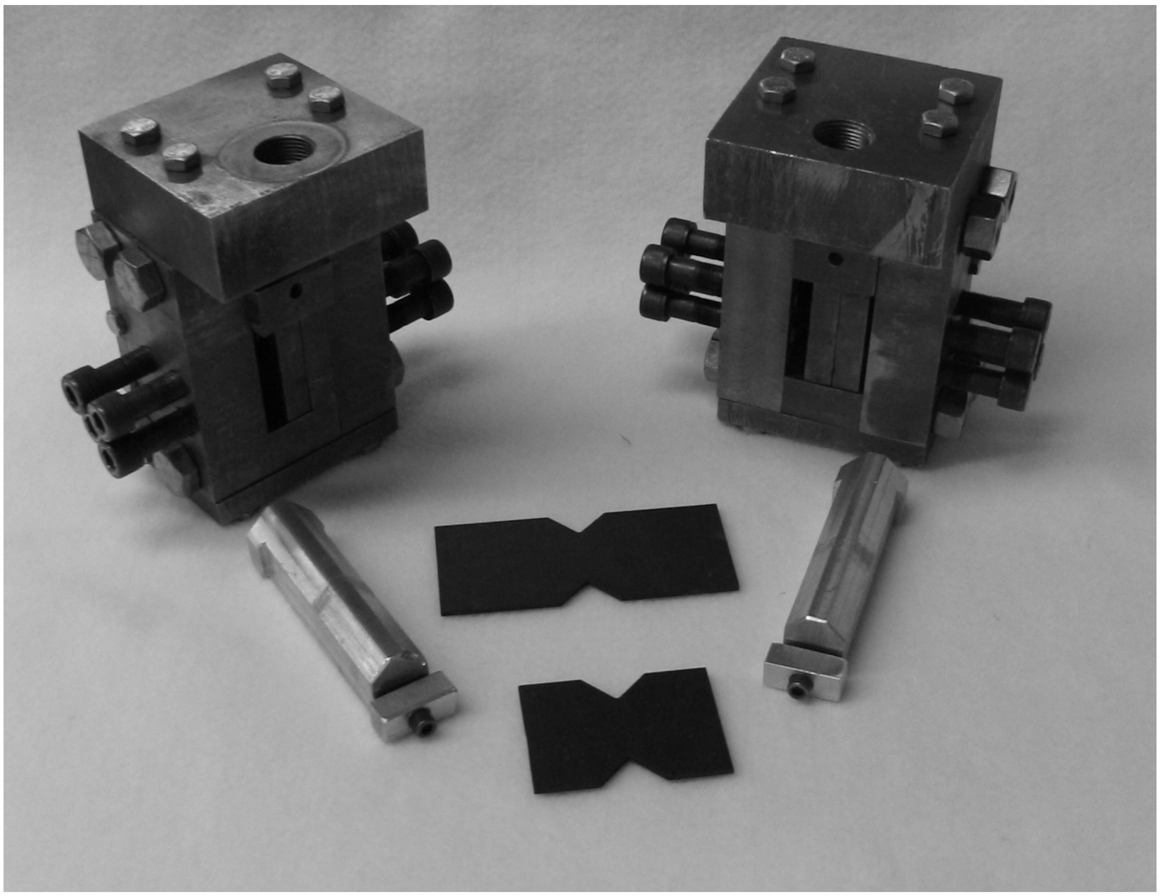


Figure 5.4 The Combined V-notch Rail Shear Test Fixture shown with two possible specimens

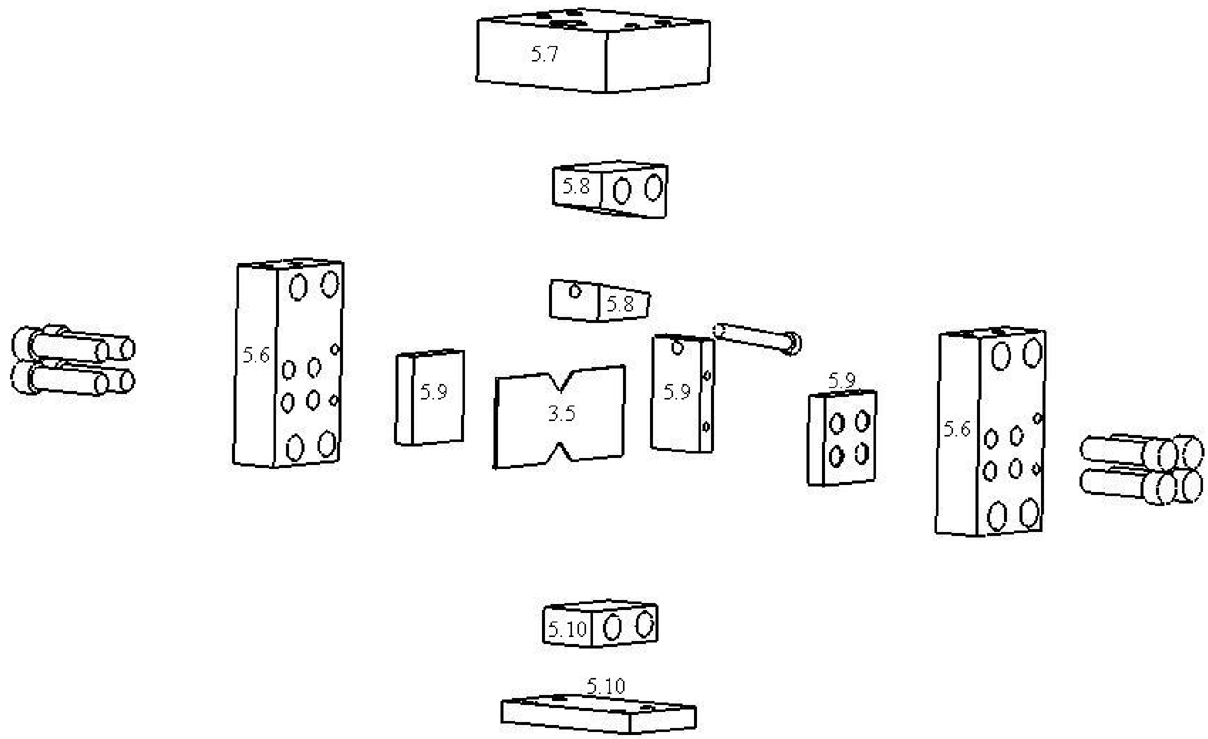


Figure 5.5 An exploded view of the Combined Loading Fixture. Numbers on the components indicate the figure where the machine drawings can be found for that component.

angle, the top edge-loading piece will move up this slope to allow the fixture to accommodate specimens of different heights. The bolt can then be tightened to secure the specimen and prevent it from rotating.

In Figure 5.9 are drawings of the back pieces and the face-loading pieces. The back piece has a hole drilled through it at a 10 degree angle and it houses the 5/16 in - 24 bolt that drives the top edge loader. The face loader piece is designed to be slightly smaller than the specimen. It can be seen when comparing the height of a specimen in Figure 3.4 or in Figure 3.5 to the height of the face loaders in Figure 5.9, the face loaders

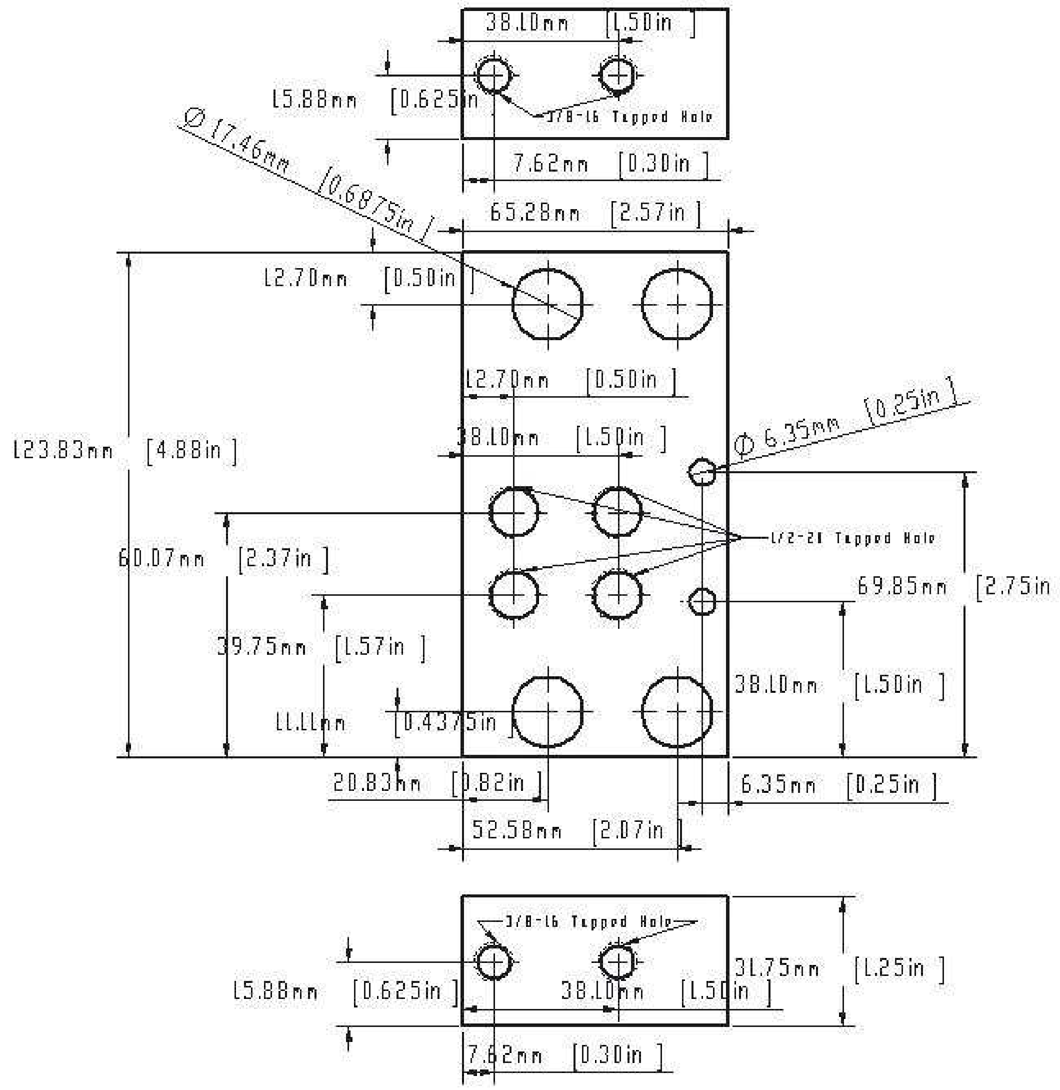


Figure 5.6 Drawings of the side pieces for the Combined Loading fixture (4 required)

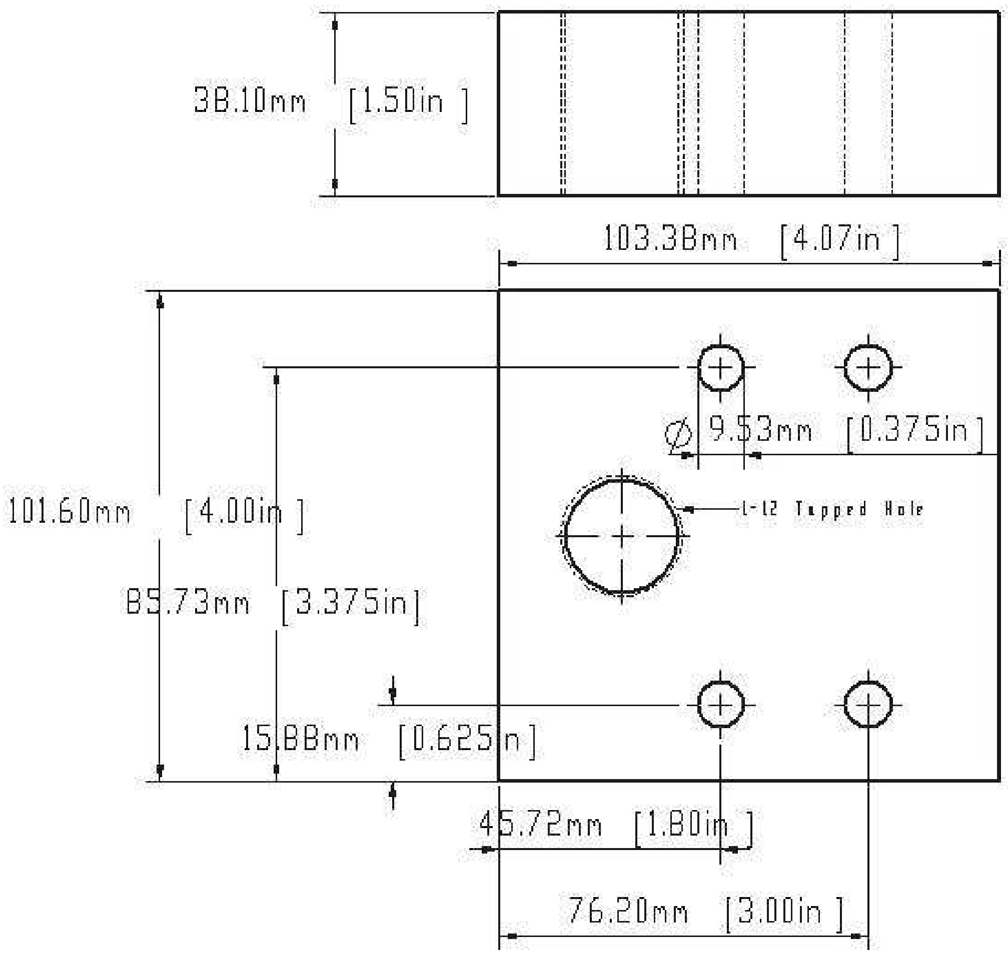


Figure 5.7 Drawings of the top pieces (2 required)

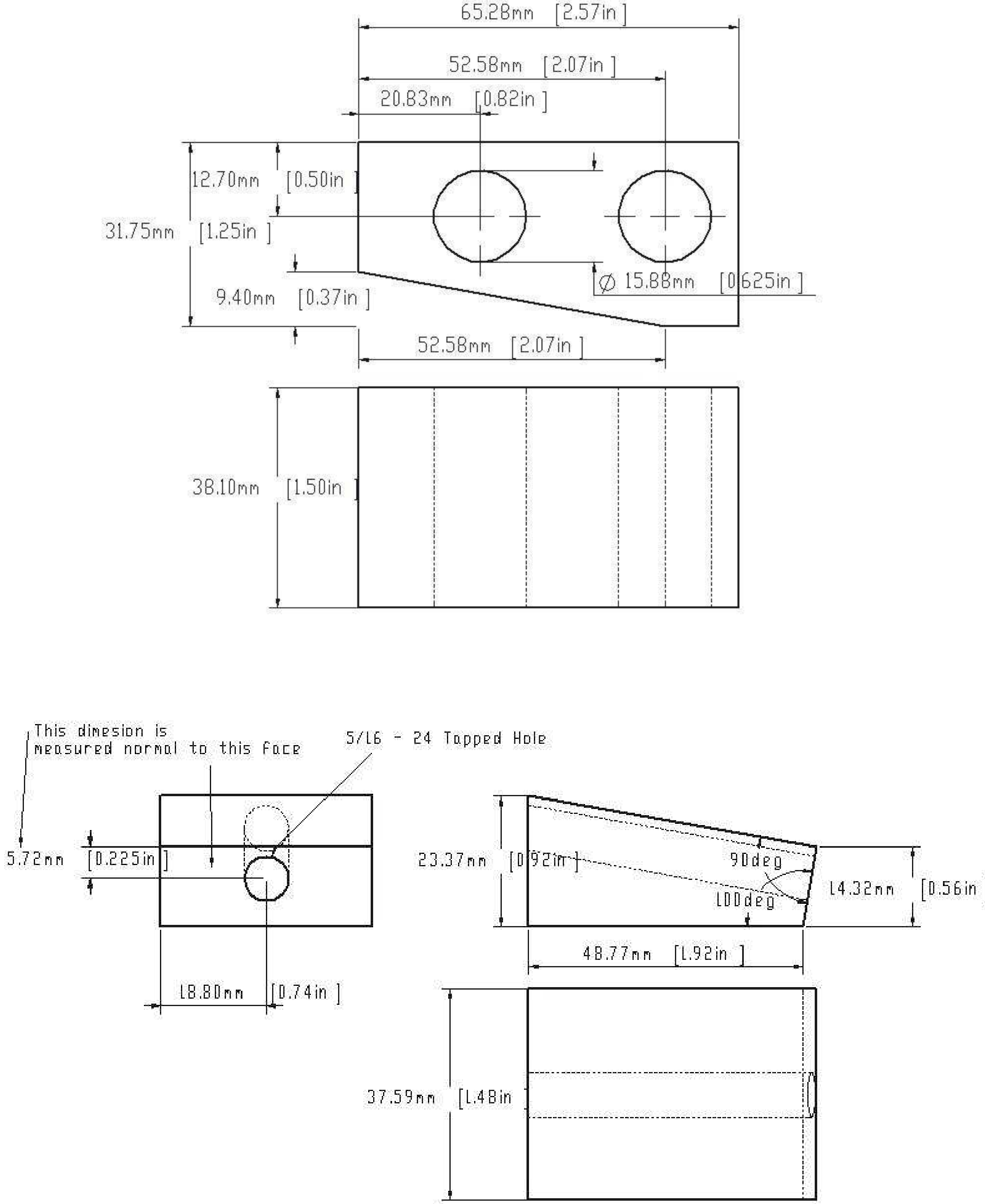


Figure 5.8 Drawings of the middle, angled pieces (top, 2 required) and the top edge-loading pieces (bottom, 2 required)

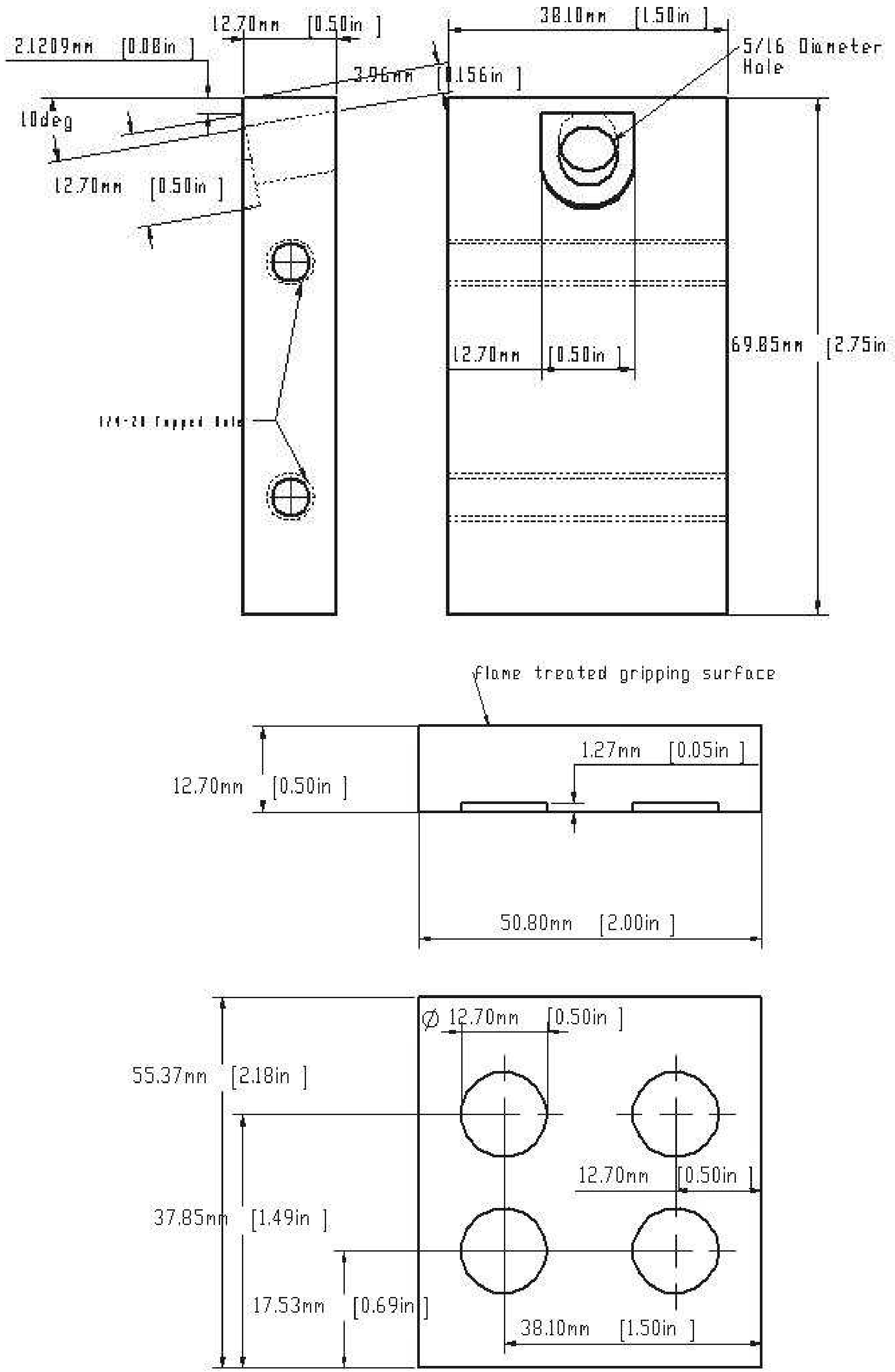


Figure 5.9 Drawings of the back pieces (top, 2 required) and the face loading pieces (bottom, 4 required)

are 0.50 mm (0.02 in) shorter than the specimens. This is done so that the edge loaders can properly contact the edges of the specimens without touching the face loaders. This height value for the face loaders was chosen also because according to ASTM 7078, the specimens can be as small as 55.62 mm (2.19 in) and still be within specifications. Making the face loaders 55.37 mm (2.18 in) still leaves 0.25 mm (0.01 in) between the face loaders and the edge loaders, ensuring that they do not touch.

Figure 5.10 shows drawings of the bottom edge-loader and the bottom pieces. The bottom edge-loader is what the bottom edge of the specimen comes in contact with when the edge-loading bolt is tightened.

5.6 Testing Procedure

All of the testing was done at room temperature using a computer-controlled MTI 50 kip electromechanical load frame, equipped with an Instron tension-compression load cell (Model #A212.201).

Before each test, the gripping surfaces on the face loaders were cleaned using a brass wire brush. This was done to ensure that the gripping surface is able to obtain the best grip possible, and is not impeded by debris from previous tests.

5.6.1 Current Standard Shear Fixture

Specimens tested using the current standard shear fixture were loaded into the test fixture by placing one of the gripping regions into the cavity of one of the halves of the test fixture. The plastic spacers (shown in Figure 1.2 on the left side) are then placed in each notch of the specimen. The plastic spacers are shaped to fit into the notches of the

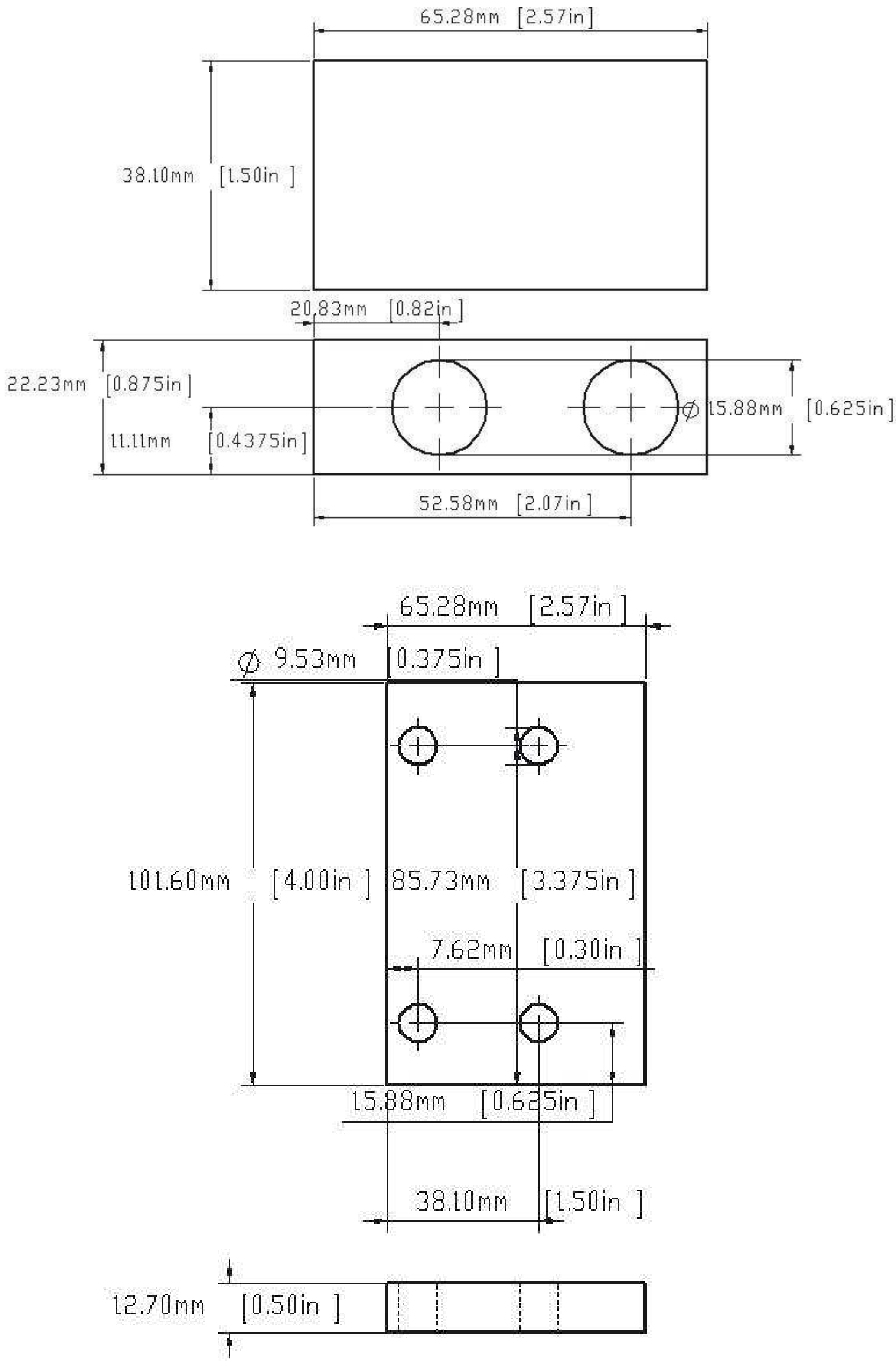


Figure 5.10 Drawings of the bottom edge-loader pieces (top, 2 required) and the bottom pieces (bottom, 2 required)

specimens, and their purpose is to hold the specimen in the correct place while it is being loaded into the fixture. The spacers are properly placed on the fixture half and specimen by placing the tabs on the ends of the spacers on the outside of the fixture then pinching the spacers together so that they hold the specimen snugly and upright. The screws on the spacers are then tightened to hold them in place. When this is done, then the spacers are holding the specimen at the correct height out the gripping cavity. This is necessary because the length of the gripping region for each specimen is 25.4 mm (1.00 in), while the depth of the cavity that holds the face-loading plates is 26.9 mm (1.06 in). The screws on each side of the fixture are then finger-tightened to properly align and center the specimen. The specimen is properly aligned by lining-up the center line ascribed on the spacers with the corresponding center line ascribed on the fixture half and the center line of the specimen. When all three center lines are lined up, then that end of the specimen is centered in the fixture. When the other spacer is also lined up in the same way then the specimen is lined up properly in the fixture half.

The face-loading screws on the fixture half are then tightened using a dial gauge torque wrench with a 125 N-m (92.1 ft-lb) capacity. The torque applied to the specimens ranged anywhere from 15 N-m (11 ft-lb) to 70 N-m (51.6 ft-lb).

Once the screws were properly tightened on the one fixture half, then the other gripping surface of the specimen was slid into the gripping cavity of the other fixture half. It is important at this point to make sure that all the tabs on the spacers are on the outside of the other fixture half and that the surfaces of the spacers are touching both the fixture halves. Doing this ensures that the halves are properly aligned, and not at an angle to each other. If the halves are not properly aligned, then the fixture will induce bending moments into the specimen and cause a premature failure. Once the two halves are properly aligned, then the face-loading bolts are finger tightened, then tightened with the torque wrench to the proper torque.

When tightening the bolts to the proper torque, it is important that every bolt be checked and re-checked. If one bolt was tightened, then the next two on the same side were tightened more, then the first bolt that was tightened will not be as tight as before. For this reason, it is important that each bolt be tightened so that all are at the proper torque without any bolts moving. If any bolts were to move, then the tightness of the rest would change, and need to be checked again.

5.6.2 The Combined Loading Test Fixture

The loading of the specimen into the Combined Loading test fixture was similar to the current shear test fixture with some exceptions. When testing 127 mm (5.00 in) long specimens, all of the ½ in -20 allen head face-loading bolts were used, but when testing 76.2 mm (3.00 in) long specimens, only the two inside bolts on each side of each half the fixture were used, while the outside bolts were left loose. This is because when a 76.2 mm (3.00 in) long specimen is loaded into the Combined Loading fixture, the gripping region only goes 25.4 mm (1.00in) into the gripping cavity, and so the outside bolts are not useful.

The loading process for the Combined Loading fixture also differs from the V-Notched fixture due to the use of the edge loaders. After the face loaders have been finger-tightened on the Combined Loading fixture, the edge loaders are also finger-tightened. Once all the face-loading bolts have been tightened with the torque wrench, then the edge loaders are tightened with a torque wrench.

It is also important to note that spacers similar to those used with the current shear fixture were fabricated for the Combined Loading fixture. The only geometric difference between these spacers was the length, which had to be increased for the larger size of the Combined Loading fixture.

After properly loading the specimen into the fixture, the assembled fixture is then placed into the load frame. It is first attached to the bottom of the load frame by screwing the 1 in -20 hole in the bottom fixture half onto a 1 in -20 rod, which is connected to the load frame. Next, the crosshead of the load frame was lowered and the test fixture was attached using a pinned connection to the upper portion of the load frame. A universal joint was included in the upper load train assembly.

All shear tests were performed with the crosshead moving at 1.27 mm/min (0.05 in/min). This was done in accordance with ASTM D 7078 [2], which recommends this crosshead speed. The average shear stress, τ, was measured as the force, *F,* applied by the load frame divided by the smallest cross-sectional area (which was measured as the thickness of the specimen multiplied by the height between the notches), *A*, or

$$\tau = F / A \tag{1}$$

Failure of a specimen was determined when the load has dropped below 75% of the maximum applied load for the individual test. The shear strength was taken as the highest stress recorded during the test.

6. EXPERIMENTAL RESULTS

6.1 Introduction

The contents of this chapter are the experimental results for the methods discussed in the previous chapter. All testing done was performed either by the V-Notched Rail Shear fixture, shown in Figure 1.2, or the Combined Loading V-Notched Rail Shear fixture, shown in Figure 5.4. The shear tests were done on multiple laminate configurations of varying thickness.

These shear tests were done on cross-ply, quasi-isotropic, and ±45 laminates. The goals of these tests were two-part. The first is to compare the performance of the Combined Loading modification to the existing fixture. The second is to compare the results of the 76.2 mm (3.00 in) long specimens to the results of the127 mm (5.00 in) long specimens that were both tested in the Combined Loading fixture.

For each laminate, at least four specimens were tested using each of the three test methods, ASTM D 7078 and Combined Loading test using 76.2 mm (3.00 in) long and 127 mm (5.00 in) long specimens. An average was taken of the shear strengths of the specimens tested using the same test method. These results can be seen in the figures and the tables shown throughout this chapter.

6.2 Friction Study

To model the fixtures and the specimens using the finite element method, experimental tests were done to determine the coefficient of friction that exists between the gripping plates and the specimens. Determining the coefficient of friction was done by testing high shear-strength specimens in the V-Notched fixture. These specimens were essentially ASTM D 7078 specimens without the notches (composite rectangles, measuring 2.2 inches by 3 inches, see Figure 3.2). These tests were done using specimens made from IM7/8552. The lay-up used was $[\pm 45]_{3s}$. These specimens were made lacking the notches to avoid stress concentrations so that the specimen would surely slip prior to failure. While the specimens did fail, they did slip noticeably prior to failing. A typical failed specimen is shown in Figure 6.1. The load at which the specimens would slip was dependent upon the torque applied to the bolts of the V-notch fixture. The ASTM standard recommends 55 N-m (40 ft-lb) as the torque applied to each bolt [2]. For these tests, torque values of 45, 55 and 65 N-m were used on different specimens. The results from these tests are shown in Table 6.1. The average loads at which the specimens slipped for the given torque were then used in the finite element model to determine the coefficient of friction between the specimens and the face loaders.

The slipping that occurs in the gripping regions of the specimen validates the finite element results for this friction study. When comparing the finite element results shown in Figure 4.2 to the experimental results seen in Figure 6.1, it can be seen that in both the finite element model and the experimental results, the same kind of slipping occurs. The scratch marks move in concentric circles around the middle of the back edge of the gripping region.

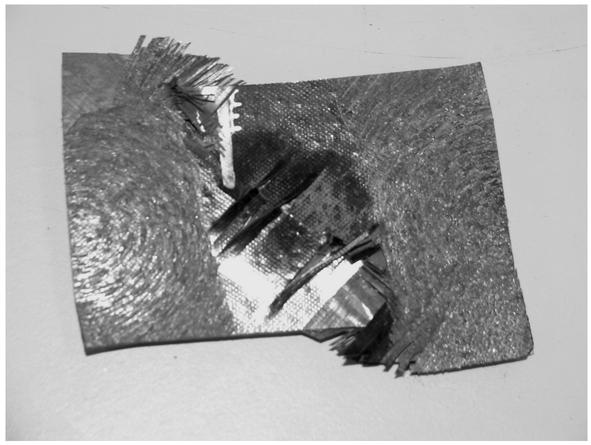


Figure 6.1 Typical result from the friction study

Table 6.1

Experimental results from the friction tests

Bolt Torque		Average Slipping Load		Standard Deviation		Coefficient of Variation
N-m	(ft-lb)	N	(lb)	N	(lb)	%
45	(33.2)	35200.0	(7913.7)	1395.3	(313.7)	3.96%
55	(40.6)	40761.4	(9164.0)	932.7	(209.7)	2.29%
65	(48.0)	47297.1	(10633.4)	4015.0	(902.6)	8.49%

6.3 Primary Results

6.3.1 Cross Ply Results

Four different cross-ply laminates were fabricated using IM7/8552. They were $[0/90]_s$, $[0/90]_{2s}$, $[0/90]_{3s}$, and $[0/90]_{4s.}$ They varied in average thickness from 1.22 mm (0.048 in) to 5.05 mm (0.2 in). The average shear strength results for the specimens cut from these laminates can be seen in Table 6.2.

In this table, under the heading "Test Method," three different test methods are listed for each laminate. They are: 7078, 3in Combined, and 5in Combined. These are the names given to the three different test methods. "7078" refers to the existing V-Notched Rail Shear Test Method described in ASTM D 7078 [2]. "3in Combined" refers to specimens that are 76.2 mm (3.00 in) long and are tested in the Combined Loading fixture. "5in Combined" refers to 127 mm (5.00 in) long specimens that are tested in the Combined Loading fixture.

Figure 6.2 shows a comparison of the average shear strengths from each test method. It also compares the shear strengths of the different cross-ply laminates. The error bars on each column represent the standard deviations in the average shear strengths.

6.3.1.1 $[0/90]_s$ results

The average shear strength for the $[0/90]_s$ specimens ranged from 92.0 MPa (13.3 ksi) to 96.3 MPa (14.0 ksi). The average shear strength for this laminate was below the average shear strength of the other cross-ply laminates.

Table 6.2

Cross-ply laminate shear strength results

		Average Shear Strength		Standard Deviation		Coefficient of Variation
Laminate	Test Method	MPa	ksi	MPa	ksi	%
$[0/90]_s$	7078	93.7	13.6	3.9	0.6	4.13%
	3in Combined	96.3	14.0	2.1	0.3	2.16%
	5in Combined	92.0	13.3	5.1	0.7	5.49%
$[0/90]_{2s}$	7078	111.7	16.2	6.9	1.0	6.18%
	3in Combined	106.9	15.5	4.2	0.6	3.92%
	5in Combined	110.8	16.1	9.1	1.3	8.17%
$[0/90]_{3s}$	7078	128.4	18.6	6.2	0.9	4.80%
	3in Combined	125.4	18.2	10.2	1.5	8.10%
	5in Combined	119.8	17.4	10.6	1.5	8.85%
$[0/90]_{4s}$	7078	131.3	19.0	19.6	2.8	14.93%
	3in Combined	128.1	18.6	8.6	1.2	6.68%
	5in Combined	136.7	19.8	9.6	1.4	7.02%

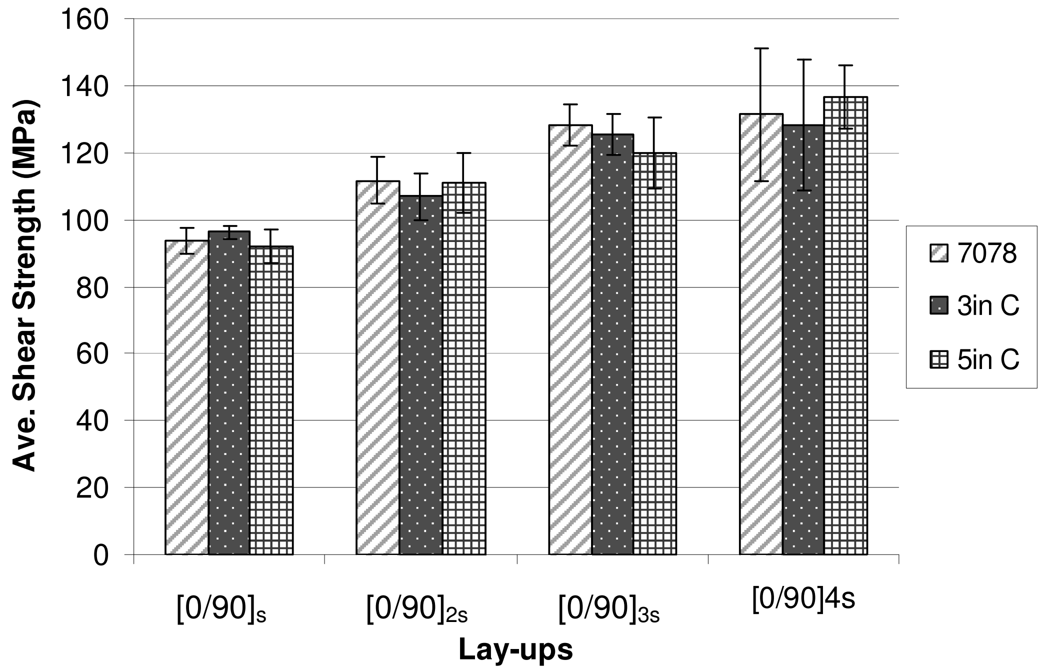


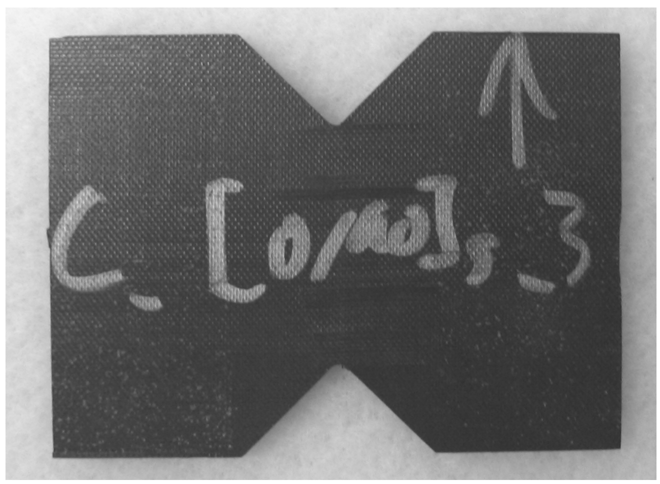
Figure 6.2 Cross-ply laminate results

Figure 6.3 shows typical specimen failures for the $[0/90]_s$ specimens, being tested using the three different test methods. From this figure, it is difficult to see the failures that occurred in these specimens. After being removed from the load frame, the specimens would relax back to their original shape; leaving little evidence that failure had occurred.

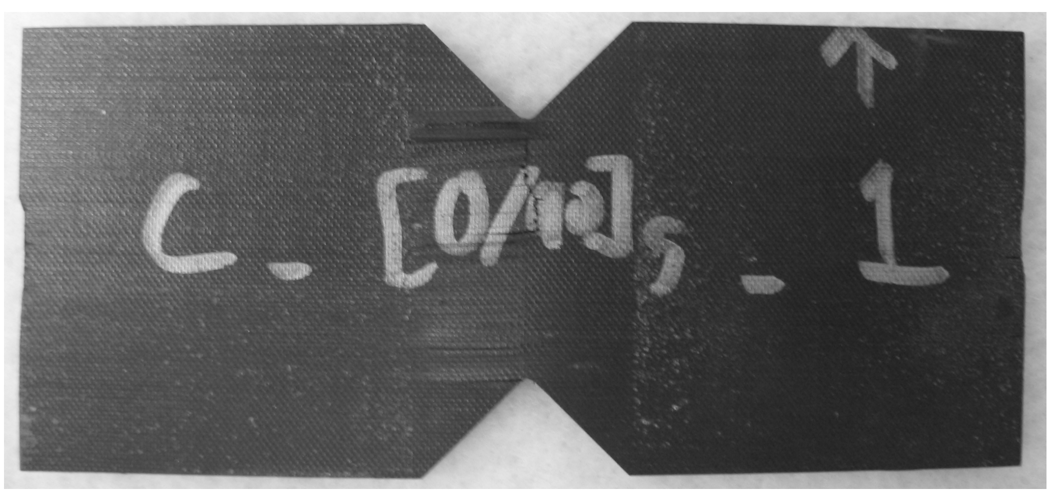
6.3.1.2 $[0/90]_{2s}$ results

The testing of the $[0/90]_{2s}$ specimens using the three test methods resulted in the average shear strength for the $[0/90]_{2s}$ specimens ranging between 106.9 MPa (15.5 ksi) and 111.7 MPa (16.2 ksi). Figure 6.4 shows typical failures that occurred for the $[0/90]_{2s}$ specimens. These failures generally result the fibers on the outside of the specimens

ASTM D 7078



76.2 mm (3.00 in) Combined Loading



127 mm (5.00 in) Combined Loading

Figure 6.3 Typical results for the $[0/90]_s$ laminate overlapping on each other. Comparing the failures of the $[0/90]_{2s}$ specimens in Figure 6.4 to the failures of the $[0/90]_s$ specimens in Figure 6.3, it can be seen that the $[0/90]_{2s}$ specimens are more permanently deformed than the $[0/90]_s$ specimens.

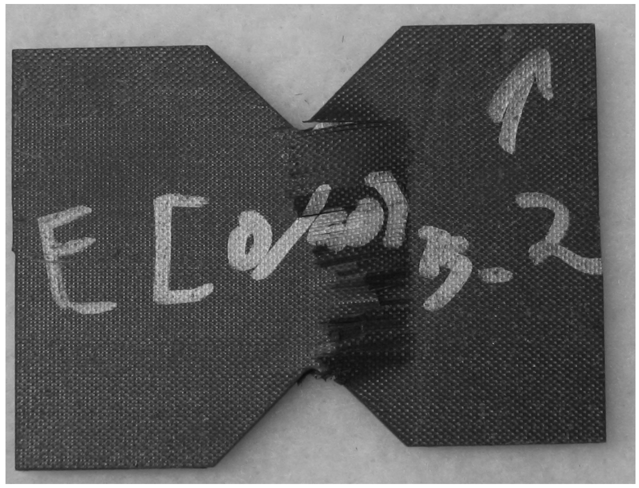
6.3.1.3 $[0/90]_{3s}$ results

The testing of the $[0/90]_{3s}$ specimens using the three different test methods resulted in the average shear strength for the $[0/90]_{3s}$ specimens ranging between 119.8 MPa (17.4 ksi) and 128.4 MPa (18.6 ksi). Figure 6.5 shows the typical failures that occurred for the $[0/90]_{3s}$ specimens. These failures are similar to the failures seen in the $[0/90]_{2s}$ laminate, but generally they show larger amounts of permanent deformation.

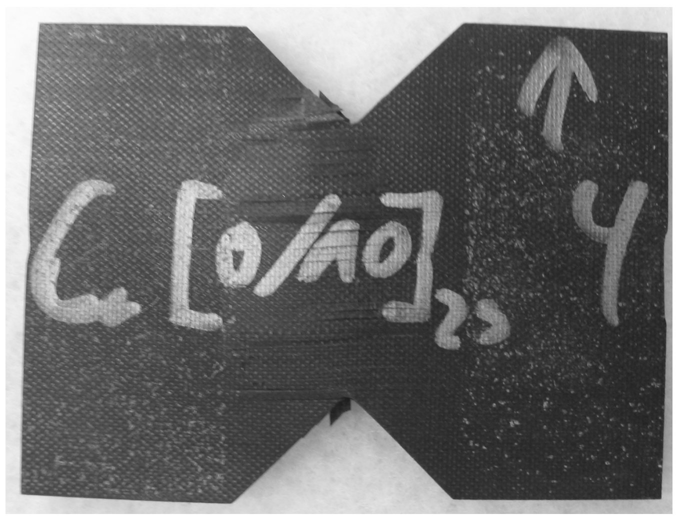
6.3.1.4 $[0/90]_{4s}$ results

Figure 6.6 shows the typical failures that occurred for the $[0/90]_{4s}$ specimens. The testing of the $[0/90]_{4s}$ specimens using the three different test methods resulted in the average shear strength for the $[0/90]_{4s}$ specimens ranging between 128.1 MPa (18.6 ksi) and 136.7 MPa (19.8 ksi). A visual inspection of the failures of the $[0/90]_{4s}$ specimens shows that these specimens have much higher amounts of permanent deformation than any of the previous cross-ply laminates.

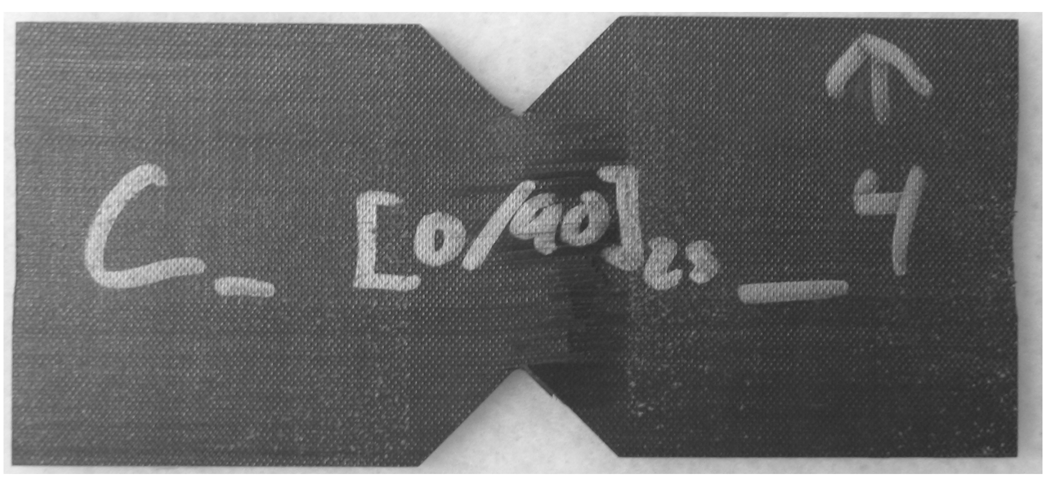
Looking at the results shown in Figure 6.2, it can be seen that none of the test methods consistently produced results with higher average shear strengths than the other two test methods. From these results it can be concluded that all of the test methods produce comparable results for these cross-ply laminates.



ASTM D 7078



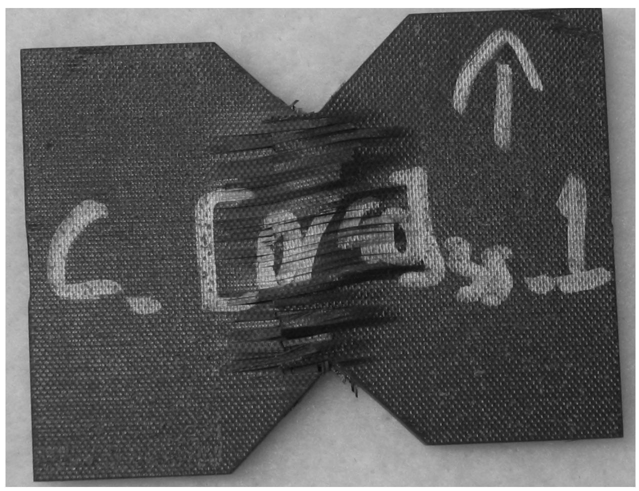
76.2 mm (3.00 in) Combined Loading



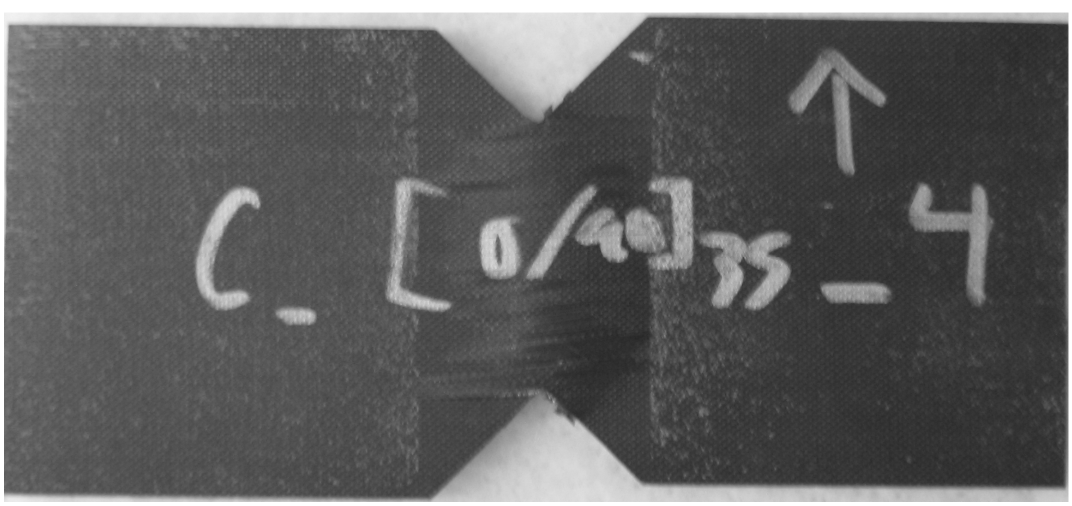
127 mm (5.00 in) Combined Loading

Figure 6.4 Typical results for the $[0/90]_{2s}$ laminate

ASTM D 7078



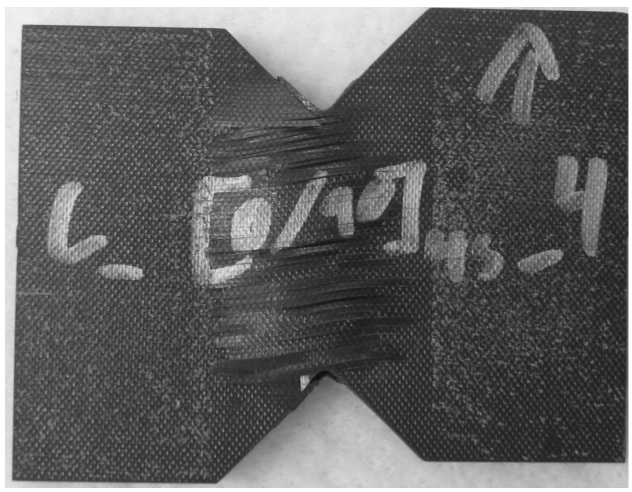
76.2 mm (3.00 in) Combined Loading



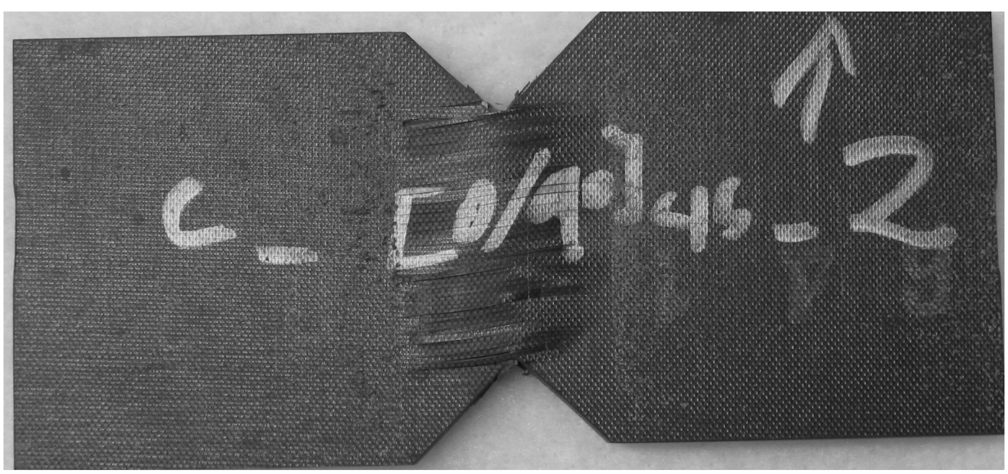
127 mm (5.00 in) Combined Loading

Figure 6.5 Typical results for the $[0/90]_{3s}$ laminate

ASTM D 7078



76.2 mm (3.00 in) Combined Loading



127 mm (5.00 in) Combined Loading

Figure 6.6 Typical results for the $[0/90]_{4s}$ laminate

6.3.2 Quasi-isotropic Results

Four quasi-isotropic laminates were tested experimentally using the three test methods, ASTM D 7078 and the Combined Loading test method using 76.2 mm (3.00 in) long specimens and 127 mm (5.00 in) specimens. The laminates tested were $[0/\pm45/90]_s$, $[0/\pm45/90]_{2s}$, $[0/\pm45/90]_{3s}$, and $[0/\pm45/90]_{4s}$. At least four specimens were tested for each test method and each laminate.

Table 6.3 shows the results for the average shear strength for all of the quasi-isotropic specimens tested. Figure 6.7 is a plot of these results with the error bars on the graph being the standard deviations in the average shear strength. It is important to note the trends that can be seen in Figure 6.7. The average shear strength results for ASTM D 7078 descend consistently as the laminate thickness increases. The 76.2 mm (3.00 in) Combined Loading modification shows a similar downward trend with increased laminate thickness, but not to the same degree as the existing standard. The 127 mm (5.00 in) Combined Loading modification does not show the same downward trend as the other two test methods, but the average shear strength remains mostly constant as the laminate thickness increases.

Figure 6.8 shows the average maximum load for each of the test methods and all of the quasi-isotropic laminates. This figure is similar to Figure 6.7, but instead of plotting the average shear strengths, it shows the average maximum loads of the specimens. This makes the trends that were spoken of earlier more apparent. The reason

Table 6.3

Quasi-isotropic laminate shear strength results

		Average Shear Strength		Standard Deviation		Coefficient of Variation
Laminate	Test Method	MPa	ksi	MPa	ksi	%
$[0/\pm45/90]_s$	7078	328.6	47.7	18.7	2.7	3.53%
	3in Combined	299.6	43.4	25.2	3.7	8.41%
	5in Combined	332.8	48.3	18.9	2.7	5.68%
$[0/\pm45/90]_{2s}$	7078	312.1	45.3	20.5	3.0	6.56%
	3in Combined	307.4	44.6	17.3	2.5	5.62%
	5in Combined	342.9	49.7	24.8	3.6	7.23%
$[0/\pm45/90]_{3s}$	7078	240.0	34.8	13.9	2.0	5.78%
	3in Combined	262.2	38.0	8.1	1.2	3.07%
	5in Combined	327.5	47.5	10.8	1.6	3.30%
$[0/\pm45/90]_{4s}$	7078	164.5	23.9	18.7	2.7	11.37%
	3in Combined	237.0	34.4	2.9	0.4	1.23%
	5in Combined	320.6	46.5	12.7	1.8	3.95%

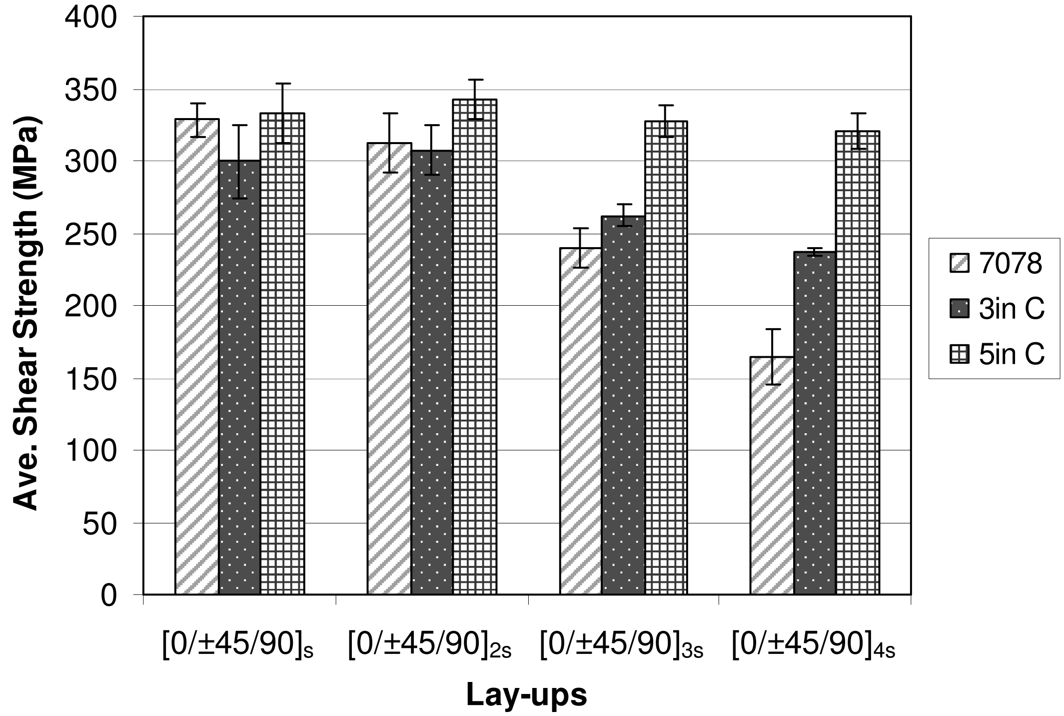


Figure 6.7 Results from the tests performed on the quasi-isotropic laminates

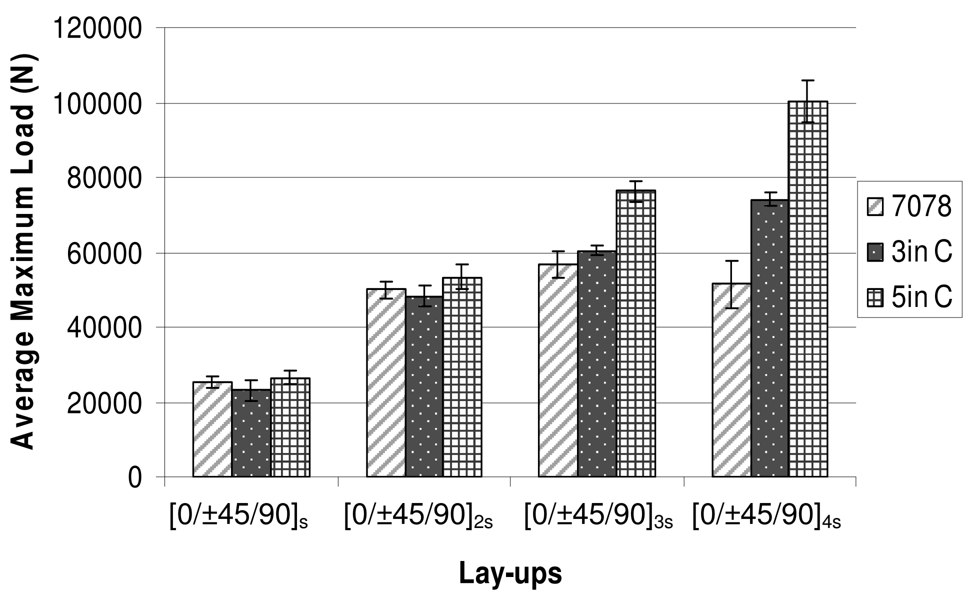


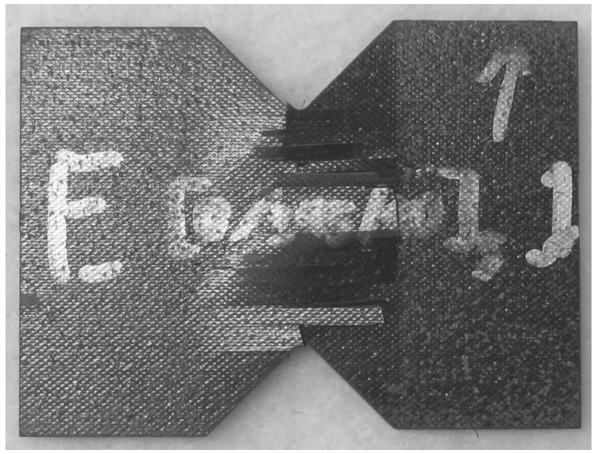
Figure 6.8 The average maximum loads for the quasi-isotropic laminates

for these trends is because of the limitations of the test methods. The existing shear test applies load only through friction using the face loaders. The maximum torque that was used on the 1/2”-20 allen head bolts that apply the gripping loads to the face loaders was 70 N-m (51.7 ft-lb). At this maximum torque, the maximum load that the existing shear test can apply to a specimen is about 53 kN (12 kip). Once the load reaches this value, the specimen will slip and rotate in the fixture. It is apparent that the ASTM D 7078 fixture cannot apply loads above 53 kN (12 kip) when looking at the ASTM D 7078 results for the [0/±45/90]2s, [0/±45/90]3s, and [0/±45/90]4s laminates in Figure 6.8.

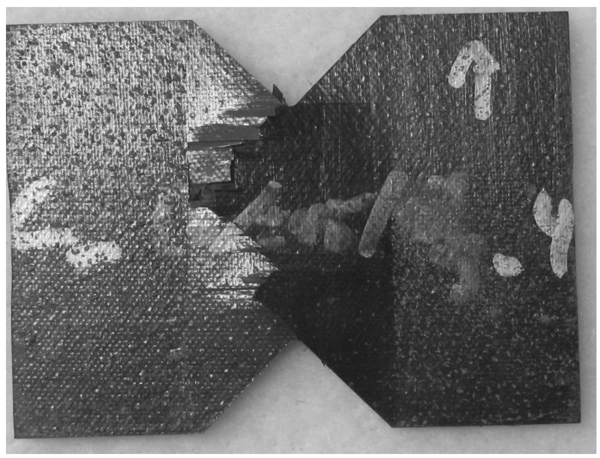
The results for the average shear strength for the quasi-isotropic specimens tested in the Combined Loading test fixture using 76.2 mm (3.00 in) long specimens have slightly more consistent results than the results obtained using the ASTM D 7078 fixture. The 76.2 mm (3.00 in) long specimens tested in the Combined Loading fixture were not able to attain the same amount of force as the 127 mm (5.00 in) long specimens because the 76.2 mm (3.00 in) long specimens have 25.4 mm (1.00 in) less gripping length on each end of the specimen.

6.3.2.1 $[0/\pm45/90]_s$ results

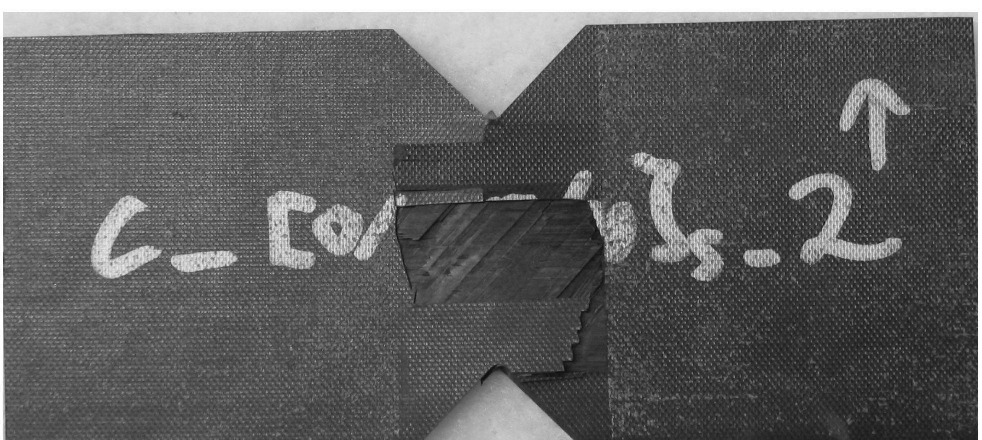
Figure 6.9 shows typical failures for the $[0/\pm45/90]_s$ specimens being tested by the three different test methods. The failure for these specimens generally exhibit splintering on the surface (the 0 degree laminas) and crushing or buckling of the ±45 degree laminas. The failure of the ±45 degree laminas cannot be seen in these pictures, but can be seen



ASTM D 7078



76.2 mm (3.00 in) Combined Loading



127 mm (5.00 in) Combined Loading

Figure 6.9 Typical results for the $[0/\pm45/90]_s$ laminate when looking at the thickness of the specimens. All of the test methods yielded similar results for this laminate.

6.3.2.2 $[0/\pm45/90]_{2s}$ results

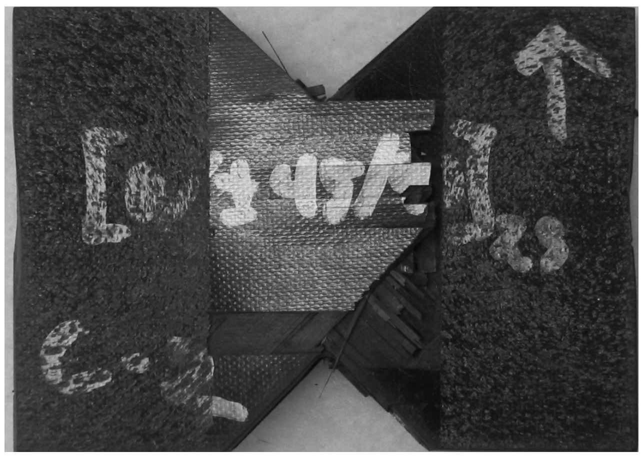
Figure 6.10 shows typical failures for the $[0/\pm45/90]_{2s}$ specimens being tested by the three different test methods. These failures show the splintering of the outer laminas and crushing and buckling of the ±45 degree laminas, similar to the failures seen in $[0/\pm45/90]_{s}$ specimens.

Significant slipping can be seen in the specimens tested using the existing shear and the 76.2 mm (3.00 in) long specimens tested in the Combined Loading fixture. No slipping was witnessed when testing $[0/\pm45/90]_{2s}$ specimens that were 127 mm (5.00 in) long.

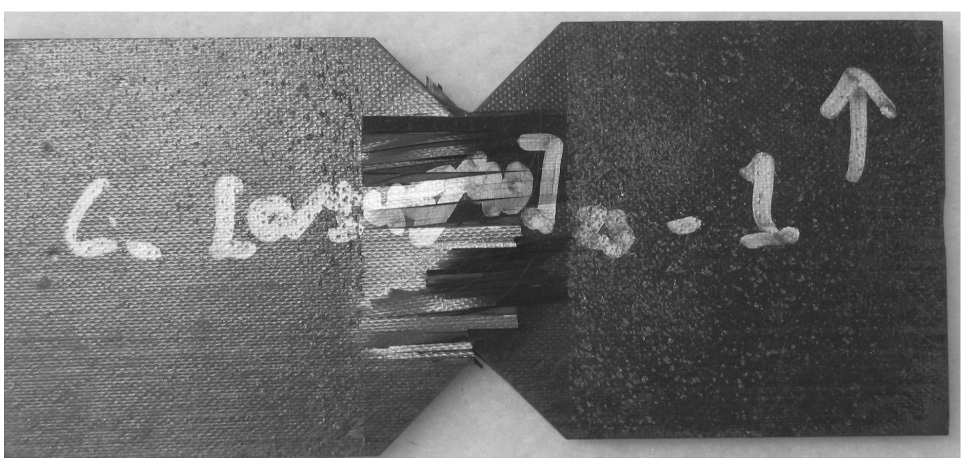
6.3.2.3 $[0/\pm45/90]_{3s}$ results

Figure 6.11 shows typical results for the $[0/\pm45/90]_{3s}$ specimens that were tested using the three different test methods. The specimens tested by the existing shear test did not fail at all, but they slipped and rotated in the fixture. This is evident in the first picture of Figure 6.11. The circular scratch marks in the gripping regions are from the rough, gripping surfaces of the face loaders. No failure was observed in any of the $[0/\pm45/90]_{3s}$ specimens that were tested using the ASTM D 7078 fixture. When testing these specimens with the ASTM D 7078 fixture, the load frame would load the specimen to a little under 53 kN (12 kip) and then the specimen would begin to slip and rotate, and would continue to rotate until the test was ended. These tests were ended after the crosshead of the load frame had displaced 7.62 mm (0.3 in).

ASTM D 7078

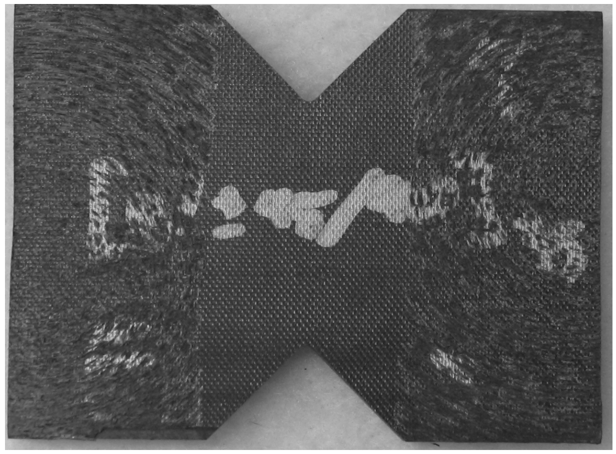


76.2 mm (3.00 in) Combined Loading

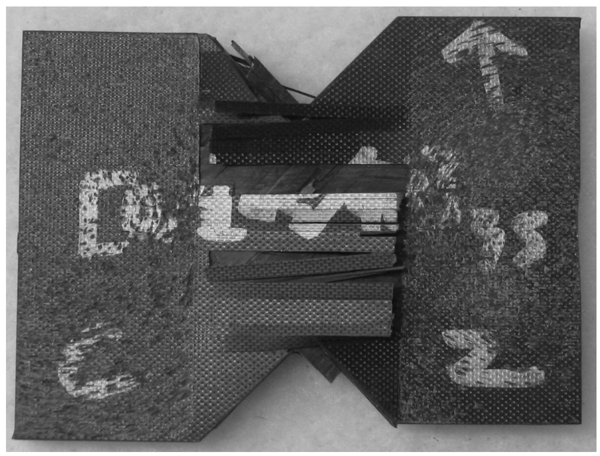


127 mm (5.00 in) Combined Loading

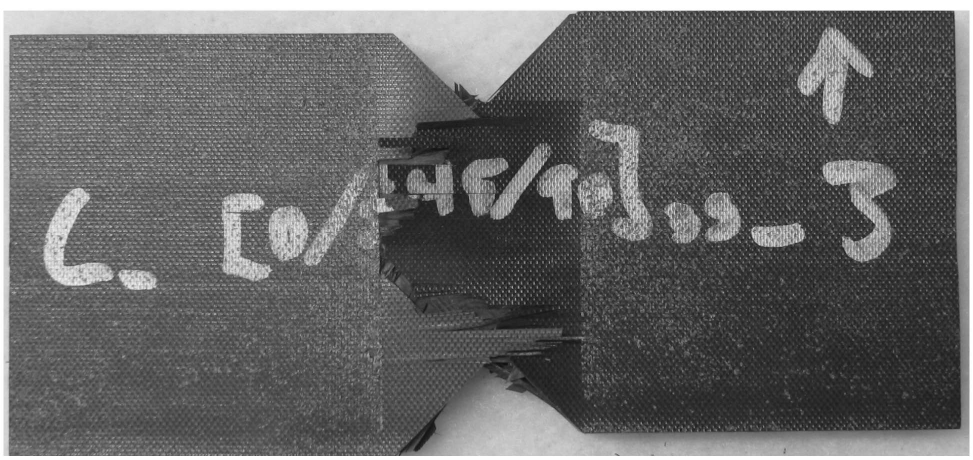
Figure 6.10 Typical results for the $[0/\pm45/90]_{2s}$ laminate



ASTM D 7078



76.2 mm (3.00 in) Combined Loading



127 mm (5.00 in) Combined Loading

Figure 6.11 Typical results for the $[0/\pm45/90]_{3S}$ laminate

The $[0/\pm45/90]_{3s}$ specimens that were 76.2 mm (3.00 in) long and were tested in the Combined Loading fixture also show signs of slipping, but to a lesser degree than those that were tested using the ASTM D 7078 fixture. The second picture in Figure 6.11 shows a typical specimen that was tested in this method. Circular scratch marks due to slipping exist, but they are not as long or pronounced as the ASTM D 7078 specimen. The results from these specimens from this laminate were the first that had a lower average shear strength than the thinner quasi-isotropic laminates when tested using the 76.2 mm (3.00 in) long specimens in the Combined Loading fixture, suggesting that the useful limits of this test method had been reached.

The 127 mm (5.00 in) long $[0/\pm45/90]_{3s}$ specimens that were tested using the Combined Loading fixture showed no signs of slipping, and they failed through the cross section. The average shear strength for the $[0/\pm45/90]_{3s}$ specimens tested by the 127 mm (5.00 in) Combined Loading test was consistent with all of the previous quasi-isotropic specimens. A typical failure can be seen in the bottom picture of Figure 6.11. It can be seen in this figure that the outer lamina does experience some failure at the grips. This is believed to be due to the stress concentrations caused by the grips. It is not believed that this failure should invalidate the test because the failure is only in the outside laminas where the fibers run transverse to the loading, and do not notably increase the strength of a quasi-isotropic laminate. Also, the results from this laminate are consistent with the results of the previous laminates.

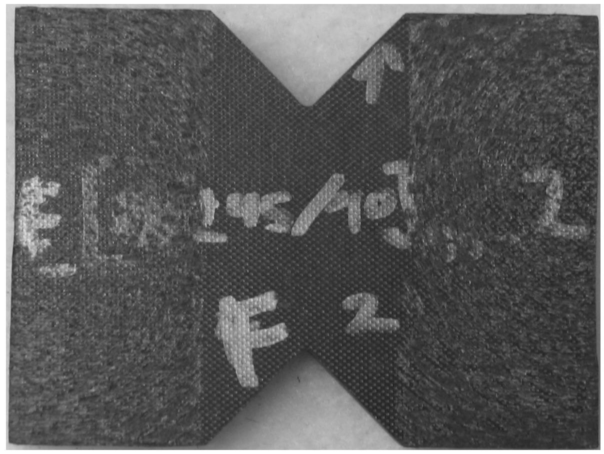
6.3.2.4 $[0/\pm45/90]_{4s}$ results

Figure 6.12 shows typical results from $[0/\pm45/90]_{4s}$ specimens tested using the three test methods. The results from these specimens confirm what was learned from the $[0/\pm45/90]_{3s}$ specimens. The existing fixture is incapable of testing specimens that require loads above 53 kN (12 kip), and while the Combined Loading fixture is able to apply higher loads than the existing fixture using 76.2 mm (3.00 in) long specimens, it does not achieve valid failures. The 127 mm (5.00 in) long specimens tested in the Combined Loading fixture, however still obtained valid failures for these specimens, which break around 100 kN (22 kip). The average shear strength for the 127 mm (5.00 in) long $[0/\pm45/90]_{4s}$ specimens is consistent with all of the previous quasi-isotropic specimens.

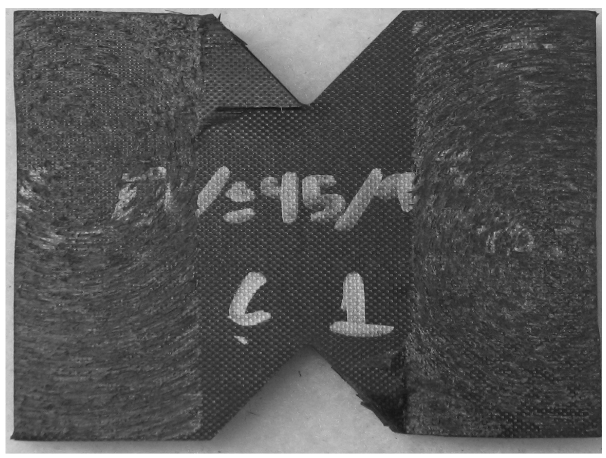
The $[0/\pm45/90]_{4s}$ specimens tested using the ASTM D 7078 fixture slipped in a similar manner as the $[0/\pm45/90]_{3s}$ specimens did when tested with the same fixture. The ASTM D 7078 fixture was able to only apply close to 53 kN (12 kip), then the specimens would slip. This can be seen in the typical result shown in the top picture of Figure 6.12.

The 76.2 mm (3.00 in) long $[0/\pm45/90]_{4s}$ specimens tested using the Combined Loading fixture slipped, similar to the specimens tested in the ASTM 7078 fixture, but the inside corners where the load was applied by the edge loaders were crushed. This can be seen in the second picture of Figure 6.12.

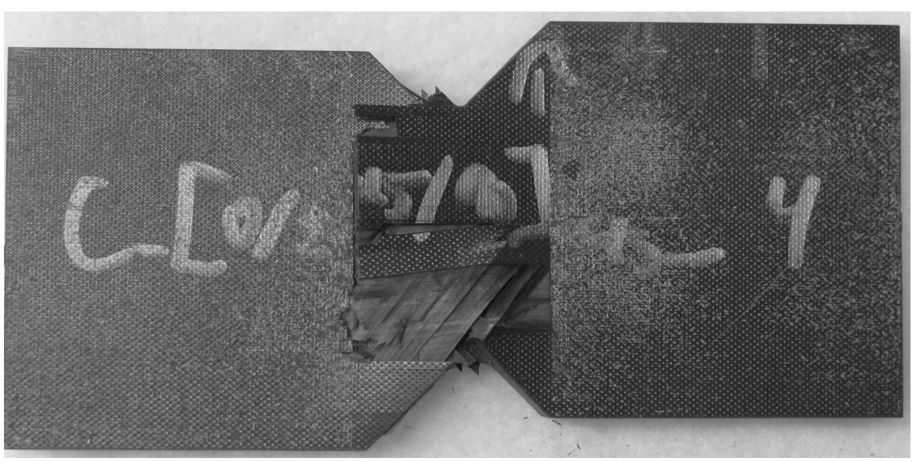
The 127 mm (5.00 in) long $[0/\pm45/90]_{4s}$ specimens tested using the Combined Loading fixture failed similar to all previous quasi-isotropic results tested with the same test method. These specimens also obtained results for the average shear strength of the laminate that were consistent with all of the previous quasi-isotropic specimens that were tested using the same test method.



ASTM D 7078



76.2 mm (3.00 in) Combined Loading



127 mm (5.00 in) Combined Loading

Figure 6.12 Typical results for the $[0/\pm45/90]_{4s}$ laminate

Looking closer at the bottom picture of Figure 6.12, impressions from the bolts can be seen in the right gripping region of the 127 mm (5.00 in) specimen. This validates the analysis done on the bolt placement in Section 4.6, and shows that the compressive stresses on the gripping surfaces are highly localized, and are not evenly distributed across the gripping regions of the specimens

After testing all the specimens from this laminate, the question as to why the 76.2 mm (3.00 in) long specimens tested using the Combined Loading fixture crushed at the corners, and the 127 mm (5.00 in) long specimens did not. Two possible causes for this difference in results are proposed.

The first possible cause for this difference is the fact that the 127 mm (5.00 in) long specimens have longer gripping regions than the 76.2 mm (3.00 in) long specimens and so the face loaders are able to support more of the load than they are with the 76.2 mm (3.00 in) long specimens. Looking back at Table 4.3 will serve as a reminder that the longer the gripping region of a specimen is, the higher the loads the face loaders are able to support. When testing the 76.2 mm (3.00 in) long specimens, the face loaders reach their limit around 53 kN (12 kip) then the specimens begin to slip. This can be seen in the ASTM D 7078 results in Figure 6.8. Because the face loaders cannot support any more load for the 76.2 mm (3.00 in) long specimens, any additional load is transferred to the specimens through the edge loaders only. For the 127 mm (5.00 in) long specimens, the upper limit of the face loaders had not been reached (which is evident because there is no slipping on the faces) and the load is more evenly distributed between the edge and face loaders. However in the case of the 76.2 mm (3.00 in) long specimens all additional load beyond the limit of the face loaders is applied only through the face loaders and so these higher loads at the corners of the test region cause the crushing seen in the specimens.

The second reason for the crushing of the corners of the 76.2 mm (3.00 in) long specimens is the fact that independent of the load applied by the load frame and the amount of slipping that occurs on the face loaders, the reactive forces applied by the edge loaders near the test region are higher for the 76.2 mm (3.00 in) long specimens than the 127 mm (5.00 in) long specimens. This answer can be explained by a figure shown in the Iosipescu shear standard, ASTM D 5379 [1]. A copy of this figure is shown in Figure 6.13.

From this figure, it can be seen that the resulting forces acting on the specimen are dependent on the dimensions of the specimen, and the total force, *P*, being applied to the specimen by the load frame. These reactive forces in the figure are for the Iosipescu test, which only uses edge loaders to apply load to the specimen. For the two Combined Loading modifications, b equals 25.4 mm (1 in), and the L equals 76.2 mm (3.00 in) for

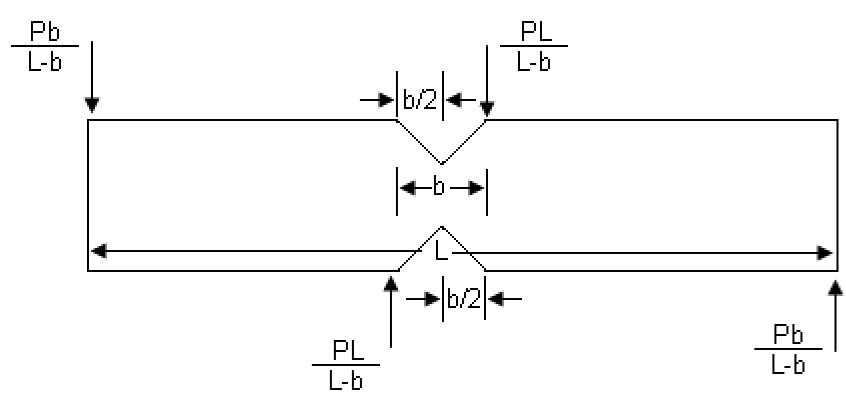


Figure 6.13 The resulting forces applied by the Iosipescu shear test

the shorter specimens and the L equals 127 mm (5.00 in) for the longer specimens. Using these values yields the following:

$$\frac{PL_{5inch}}{L_{5inch}-b} = P\frac{5}{5-1} = P\frac{5}{4} = 1.25P$$
$$\frac{PL_{3inch}}{L_{3inch}-b} = P\frac{3}{3-1} = P\frac{3}{2} = 1.50P \tag{6.1}$$

From the results in equation 6.1, it can be seen that for the 76.2 mm (3.00 in) long specimens, the load applied at the corners of the test region are 25% higher than those applied on the 127 mm (5.00 in) long specimens. The higher loads in the shorter specimens could cause crushing to occur where there would not be any crushing with a longer specimen under the same total load.

6.3.3 ±45 Results

Four ±45 laminates were tested experimentally using the three different test methods, ASTM D 7078 and the Combined Loading test fixture using 76.2 mm (3.00 in) long specimens and 127 mm (5.00 in) long specimens. The laminates tested were $[\pm45]_{2s}$, $[\pm45]_{3s}$, $[\pm45]_{4s}$, and $[\pm45]_{5s}$. At least four specimens were tested for each test method and each laminate.

Table 6.4 shows the average shear strength results for all of the ±45 specimens tested. Figure 6.14 is a plot of these results with the error bars on the graph being the standard deviations in the average shear strengths. The trend that is apparent in this figure is the downward trend in average shear strength with an increase in laminate thickness for

Table 6.4

±45 laminate shear strength results

		Average Shear Strength		Standard Deviation		Coefficient of Variation
Laminate	Test Method	MPa	ksi	MPa	ksi	%
$[\pm 45]_{2s}$	7078	397.1	57.6	10.6	1.5	12.34%
	3in Combined	346.4	50.2	29.3	4.3	8.46%
	5in Combined	376.8	54.7	26.3	3.8	6.97%
$[\pm 45]_{3s}$	7078	394.7	57.2	39.8	5.8	10.08%
	3in Combined	356.4	51.7	11.0	1.6	3.10%
	5in Combined	371.6	53.9	9.3	1.4	2.51%
$[\pm 45]_{4s}$	7078	313.2	45.4	10.6	1.5	3.40%
	3in Combined	298.6	43.3	4.4	0.6	1.48%
	5in Combined	348.8	50.6	13.2	1.9	3.79%
$[\pm 45]_{5s}$	7078	274.8	39.9	20.1	2.9	7.31%
	3in Combined	NOT TESTED				
	5in Combined	324.0	47.0	2.6	0.4	0.81%

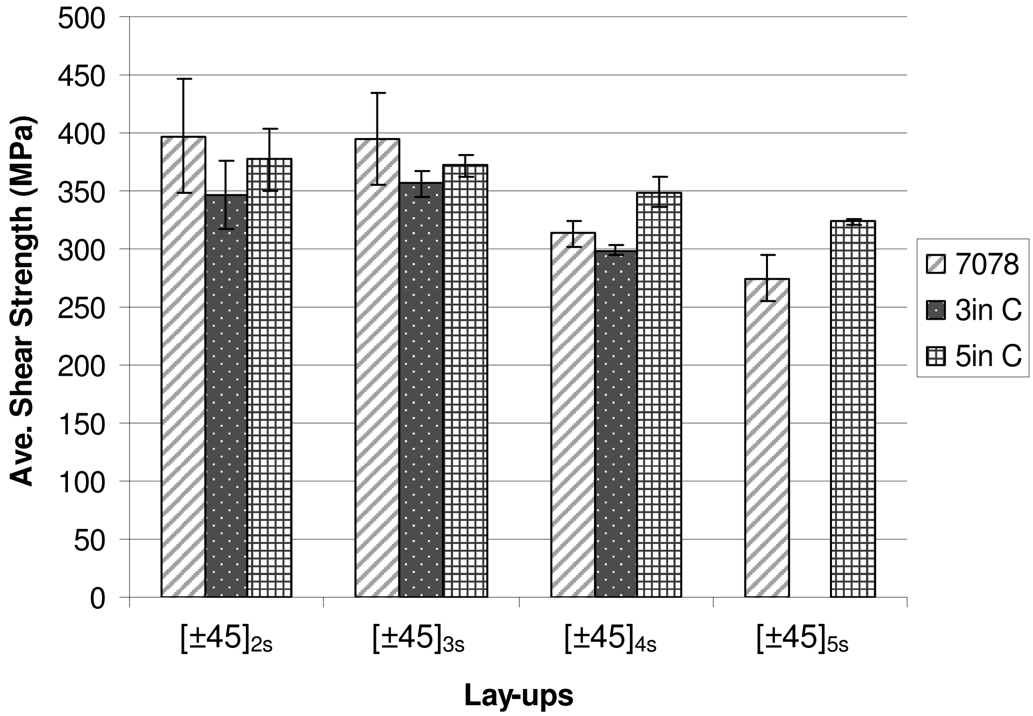
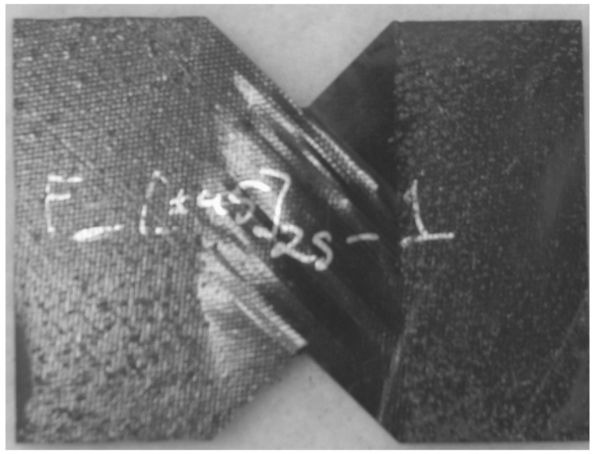


Figure 6.14 Results from the tests performed on the ±45 laminates

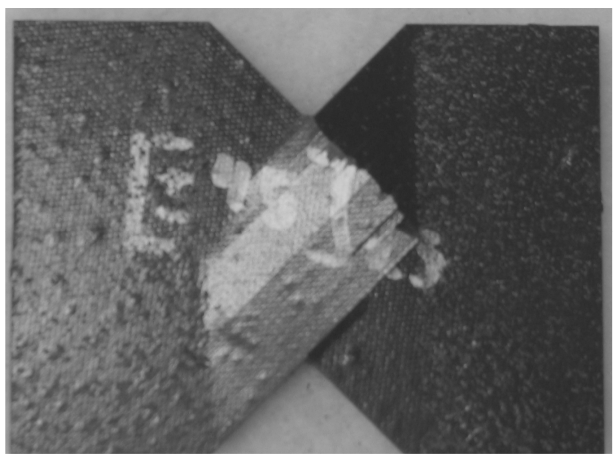
all the test methods. The ASTM D 7078 and the Combined Loading 76.2 mm (3.00 in) long both report a greater reduction in average shear strength with increased thickness than the 127 mm (5.00 in) long specimens, which show a more gradual decrease in average shear strength. The results for the first two laminates, $[\pm 45]_{2s}$ and $[\pm 45]_{3s}$ are consistent for all of the test methods. The results for the following laminates show a decline in the average shear strength.

6.3.3.1 $[\pm 45]_{2s}$ Results

Figure 6.15 shows typical failures for the $[\pm 45]_{2s}$ specimens tested using the three test methods. Typical failures have cracks running from the notches at a 45 degree angle to the grips. This type of failure is not only typical for the specimens made from this laminate, but is typical for all of the ±45 laminates. The reason for this type of failure is the lay-up of the specimens and the state of stress in the test section. In Chapter 4 the finite element results show that the state of stress between the notches for the ±45 laminates is dominated by in-plane shear stresses. When this state of stress is transformed to the orientation of the fibers (±45 degrees), the result is tensile and compressive stresses on the fibers. Fiber reinforced composites are stronger when the fibers are placed in tension than compression, so the fibers that are being compressed in the specimens fail first and there are failures running at 45-degree angles from the notches.



ASTM D 7078



76.2 mm (3.00 in) Combined Loading

127 mm (5.00 in) Combined Loading

Figure 6.15 Typical results for the $[\pm 45]_{2s}$ laminate

6.3.3.2 $[\pm 45]_{3s}$ results

Figure 6.16 shows typical failures for the $[\pm 45]_{3s}$ specimens tested using the three test methods. These results are similar to the results seen in the $[\pm 45]_{2s}$ specimens. One difference is the slight slipping that can be seen in the ASTM D 7078 and the 76.2 mm (3.00 in) long Combined Loading examples.

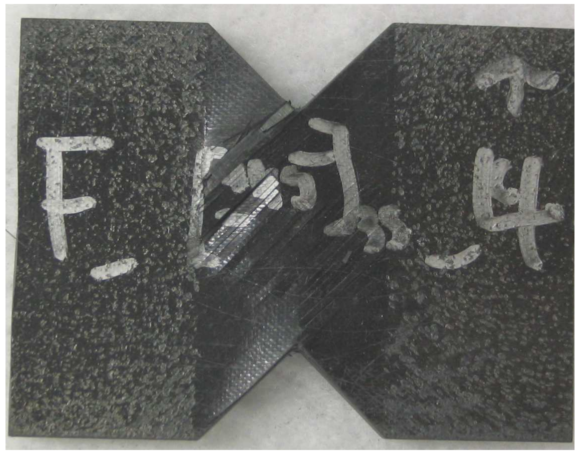
6.3.3.3 $[\pm 45]_{4s}$ results

Figure 6.17 shows typical failures for the $[\pm 45]_{4s}$ specimens tested using the three test methods. These results show larger amounts of slipping for all of the test methods. The ASTM D 7078 and 76.2 mm (3.00 in) long Combined Loading specimens show large amounts of slipping, while the 127 mm (5.00 in) long Combined Loading specimens show some small amount of slipping near the gage section. It is difficult to see any failure in the ASTM D 7078 specimen, but there is a small crack running from the top notch to the right gripping surface. The failures in the 76.2 mm (3.00 in) long Combined Loading specimens are also harder to visually detect.

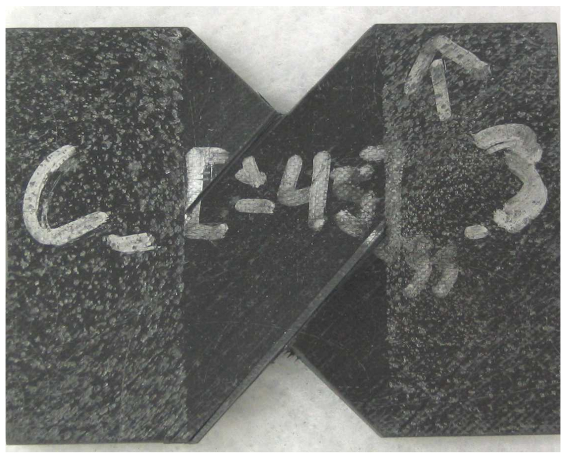
6.3.3.4$[\pm 45]_{5s}$ results

Figure 6.18 shows typical failures for the $[\pm 45]_{5s}$ specimens tested using only two of the test methods. Only the ASTM D 7078 and the 127 mm (5.00 in) long Combined Loading specimens were tested for this laminate. The 76.2 mm (3.00 in) Combined Loading test method was omitted for this laminate because of its underwhelming results in all of the previous ±45 laminates.

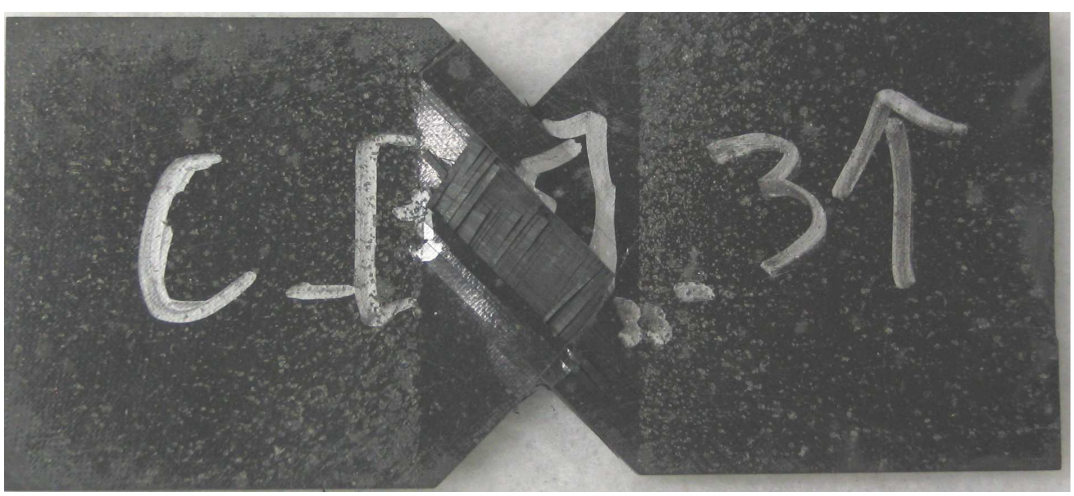
The ASTM D 7078 tests resulted in large amount of slipping and small failures. A Typical failure is shown in Figure 6.18.



ASTM D 7078

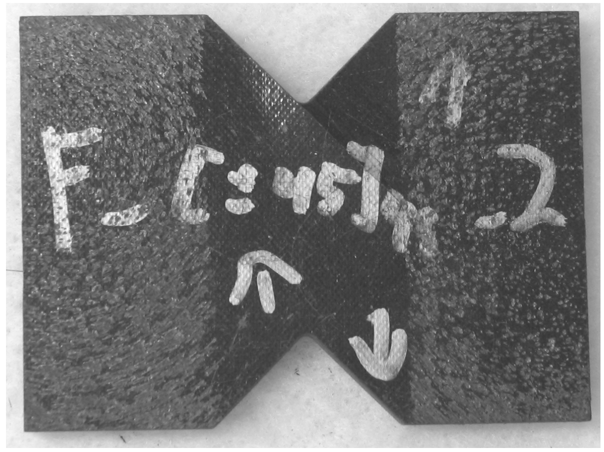


76.2 mm (3.00 in) Combined Loading

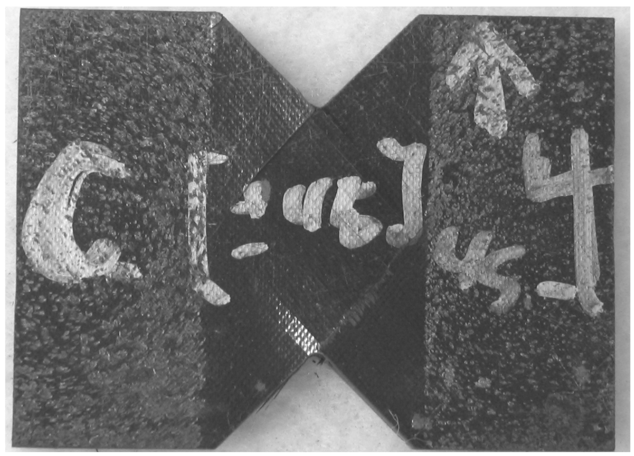


76.2 mm (3.00 in) Combined Loading

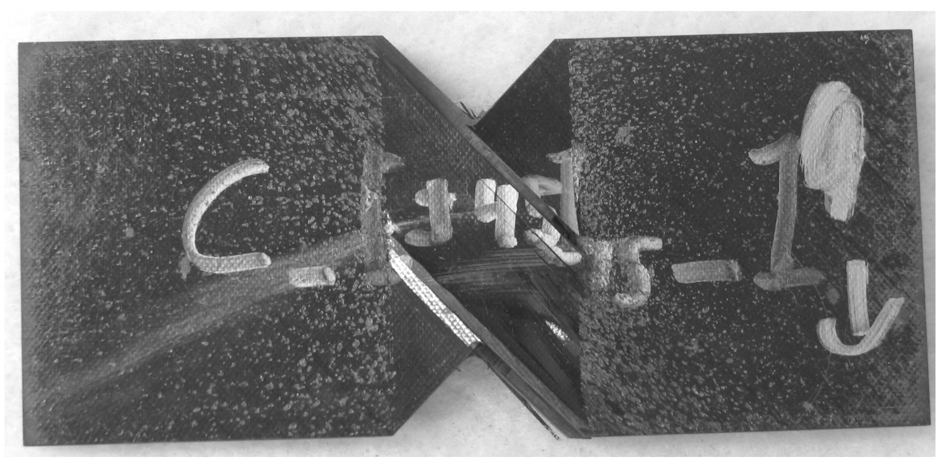
Figure 6.16 Typical results for the [±45]$_{3s}$ laminate



ASTM D 7078

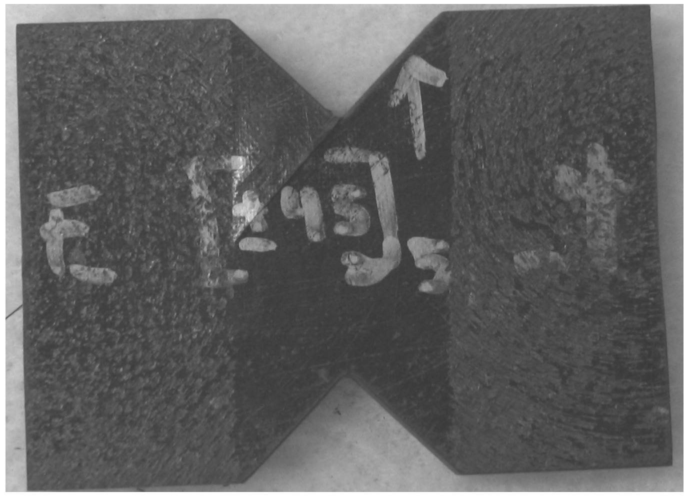


76.2 mm (3.00 in) Combined Loading



127 mm (5.00 in) Combined Loading

Figure 6.17 Typical results for the [±45]$_{4s}$ laminate



ASTM D 7078

127 mm (5.00 in) Combined Loading

Figure 6.18 Typical results for the $[\pm45]_{5s}$ laminate

The 127 mm (5.00 in) long Combined Loading specimens show signs of slipping near the test region in the corners that are not being loaded by the edge loaders. In the bottom picture of Figure 6.18 the gripping region to the right of the upper notch and the gripping region to the left of the bottom notch show signs of slipping. These areas are being pulled away from the edge loaders and so the only constraints holding these parts of the specimens are the face loaders.

7. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Conclusions

The purpose of this research has been to determine if the Combined Loading Modification to the V-Notched Rail Shear Test would be a viable solution to the limitations of the current V-Notched Rail Shear Test. Finite element analyses have been performed to determine the states of stress that exist in the current V-Notched Rail Shear Test and the Combined Loading Test. The Combined Loading test fixture was compared experimentally using 76.2 mm (3.00 in) long and 127 (5.00 in) long specimens to the V-Notched test fixture.

The laminate effects study done using the finite element method suggests that there are minimal differences between the states of stress for 76.2 mm (3.00 in) long and 127 mm (5.00 in) long specimens tested in the Combined Loading fixture that are of the same laminate. The finite element results suggest that the state of in-plane shear stress is highly uniform between the notches for all of the laminates investigated.

The results from the finite element analysis also showed that the transverse normal stresses between the notches in the cross-ply and quasi-isotropic laminates are low and highly uniform. The ±45 laminate modeled in the Combined Loading fixture had slightly higher transverse normal stresses between the notches. These stresses range between -3.75% and 11.25% of the average shear stress in-between the notches.

The axial normal stresses from notch to notch for the cross-ply laminate modeled in the Combined Loading fixture were low and highly uniform. The axial normal stresses from notch to notch for the quasi-isotropic laminate and the ±45 laminate were also uniform but both laminates exhibited compressive stresses in-between the notches.

A comparison between the effects of face-loading only and edge-loading only showed that the cause of the compressive axial normal stresses that exist in the quasi-isotropic and the ±45 laminates is the edge loaders. This comparison between face-loading only and edge-loading only also showed that the edge loaders are the cause of the higher transverse normal stresses in-between the notches of the ±45 laminate.

The thickness effects study done using the finite element method suggests that for the cross-ply laminate, all three test methods produce similar, uniform states of in-plane shear stress and all are equally valid. For the quasi-isotropic laminate, the Combined Loading test using 127 mm (5.00 in) long specimens had the most uniform state of in-plane shear followed by the Combined Loading test using 76.2 mm (3.00 in) long specimens. For the ±45 laminate, the Combined Loading test method using both 76.2 mm (3.00 in) long and 127 mm (5.00 in) long specimens had equally valid states of in-plane shear stress. The existing V-Notched Rail Shear test had the least uniform state of in-plane shear stress through the thickness for the quasi-isotropic and the ±45 laminates.

In the experimental study, the Combined Loading modification to the V-Notched Rail Shear test method using 127 mm (5.00 in) long specimens produced the most consistent average shear strengths for similar laminates of different thickness than either of the other test methods analyzed in this study. The Combined Loading Test using 127 mm (5.00 in) long specimens was able to obtain results equally valid as the existing shear test on weaker laminates like the cross-ply laminates and the thin quasi-isotropic laminates, and it resulted in higher average shear strength results on all of the stronger laminates such as the thicker quasi-isotropic laminates and the thicker ±45 laminates. The existing shear test was not able to properly constrain the stronger specimens and the specimens would slip and rotate in the grips. The Combined Loading test method was able to load the $[0/\pm45/90]_{4s}$ 127 mm (5.00 in) specimens up to 100 kN (22.5 kip), while the V-Notched test fixture would allow specimens to slip when the load applied by the load frame approached 53 kN (12 kip).

The Combined Loading modification to the V-Notched Rail Shear test using 76.2 mm (3.00 in) long specimens was able to constrain stronger specimens that the existing shear test could not. However, for the strongest of specimens such as the $[\pm45]_{4s}$ and the $[0/\pm45/90]_{4s}$, the Combined Loading fixture using 76.2 mm (3.00 in) long specimens was unable to obtain average shear strengths consistent with the thinner laminates. For the thicker, quasi-isotropic and ±45 specimens the Combined Loading test would allow the 76.2 mm (3.00 in) long specimens to slip or would crush the corners, thus invalidating the results.

7.2 Recommendations for Future Work

The current prototype of the Combined Loading fixture uses ½"-20 inch allen head bolts to apply the normal forces for the face loaders. Research should be done to determine if larger bolts can be used to apply these normal forces. The use of larger bolts would create more evenly distributed compressive stresses on the face of the specimens. This would reduce the localized compressive stresses discussed in Chapter 4. The use of larger bolts would also create larger normal stresses for the same applied torque, according to equation 4.1.

A study should also be done to determine where the most effective location would be to place the bolts for the face loaders. The locations for these bolts on the current prototype were chosen arbitrarily. It was assumed that the compressive stresses would be even across the gripping surface of the face loaders when in fact the analysis leading to Figure 4.7 shows that it is not. The results shown in Figure 4.7 suggest that the bolts would be more effective if they were placed nearer to the corners of the face loaders.

Research should also be done to determine what load the allen head bolts truly apply to the face loaders for a specified torque. This research would determine the validity of the gripping loads determined by equation 4.1.

Finally, computational modeling should be performed to determine the effects the gripping loads applied by the allen head bolts have on the state of stress in the specimens.

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